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July 1, 1969 to December 31, 1969

ANALYSIS AND DESIGN OF A CAPSULE LANDING SYSTEM AND SURFACE VEHICLE CONTROL SYSTEM FOR MARS EXPLORATION

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ABSTRACT

Investigation of problems related to the landing and controlling of a mobile planetary vehicle according to a systematic plan of exploration of Mars has been undertaken. Problem areas receiving consideration include: updating of atmosphere parameters during entry, adaptive trajectory control, unpowered aerodynamic landing, terrain modeling and obstacle sensing, vehicle design,dynamics and attitude control, and chromatographic systems design concepts. The specific tasks which have been undertaken are defined and the progress which has been made during the interval July 1, 1969 to December 31, 1969 is summarized. Projections for work to be undertaken during the next six months period are included.

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Analysis and Design of a Capsule Landing System and Surface Vehicle Control System for Mars Exploration

I. Introduction

The planned exploration of the planet Mars in the 1970's involves the landing of an excursion module on the martian surface. Following a successful landing, the exploration of the martian surface would be promoted considerably if the excursion model is mobile and if its motion can be controlled according to a specific plan of exploration. Contributing to the formidable problems to be faced by such a mission are the existence of an atmosphere whose parameters are at this time rather uncertain within broad limits and the information transmission delay time between Martian and Earth control units. With the support of NASA Grant NGL-33--18-091, a number of important problems originating with the factors noted above have been investigated by a faculty-student team at Rensselaer.

The problems under study fall into two broad categories: (a) capsule landing and (b) control of a mobile exploration unit, from which a considerable number of specific tasks have been defined. This progress report describes the tasks which have been undertaken and documents the progress which has been achieved in the interval July 1, 1969 to December 31, 1969 and projects activity for the next period ending June 30, 1970.

II. Definition of Tasks

The uncertainty in martian atmosphere parameters and the delay time (order of ten minutes) in round trip communication between Mars and Earth underlie unique problems relevant to martian and/or other planetary explorations. All phases of the mission from landing the capsule in the neighborhood of a desired position to the systematic traversing of the surface and the attendant detection, measurement, and analytical operations must be consummated with a minimum of control and instruction by earth based units. The delay time requires that on board systems capable of making rational decisions be developed and that suitable precautions be taken against potential catastrophic failures. Five major task areas, which are in turn divided into appropriate sub-tasks, have been defined and are listed below.

A. Trajectory Control - If updated martian atmosphere parameters can be obtained during entry, an adaptive trajectory control system can be used to achieve the desired velocity, range and altitude parameters prior to the final landing phase. This task is concerned with methods by which to achieve the desired terminal conditions given the availability of updated atmospheric parameters.

B. Unpowered Aerodynamic Landing. The existence of an atmosphere on Mars, slight as it is, offers an opportunity for unpowered landing of the capsule through the use of aerodynamic forces. The objective of this task is to investigate the feasibility of devices utilizing aerodynamic forces to effect an acceptable landing approach and touchdown.

C. Surface Navigation and Path Control. Once the capsule is landed and the roving vehicle is in an operational state, it is necessary that the vehicle can be directed to proceed under remote control from the landing site to specified positions on the martian surface. This task is concerned with the problems of terrain modeling, path selection and navigation between the initial and terminal sites when major terrain features precluding direct paths are to be anticipated. On board decision making capability must be designed to minimize earth control responsibility except in the most adverse circumstances.

D. Vehicle Configuration, Control, Dynamics, Systems and Propulsion. The objectives of this task are to investigate problems related to the design of a roving vehicle for Mars exploration with respect to configuration; motion and attitude control; obstacle avoidance; control, information and power systems; and propulsion systems. In addition, the design concepts must accommodate the equipment and instruments required to automate the vehicle and to perform the scientific objectives of the mission.

E. Chemical Analysis of Specimens. A major objective of martian surface exploration will be to obtain chemical, biochemical or biological information. Most experiments proposed for the mission require a general duty, chromatographic separator prior to chemical analysis by some device. The objective of this task is to generate fundamental data and concepts required to optimize such a chromatographic separator according to the anticipated mission.

III. Summary of Results

Task A. Adaptive Trajectory Control

Task A.I. Trajectory Control of Mars Entry by Flight Angle - K. Yong
Faculty Advisor: Prof. C.N. Shen

The Mars entry problem has been recently investigated using sensitivity analysis to handle uncertainties in the estimates of the Martian atmosphere, Ref. 1. The purpose of the problem requires satisfying specified constraints at a given terminal altitude in order to assure a successful soft landing on the Martian surface. The two most important constraints to be satisfied at the terminal altitude are the range angle and velocity. It is desired that the terminal range error due to the difference between the reference atmospheric model and the updated actual atmospheric model be as small as possible, and that the terminal velocity should not exceed 1000 fps for a safe soft landing. One very effective way being investigated involves using a discrete change of the ballistic coefficient at a fixed altitude accompanied by applying an impulsive thrust perpendicular to the direction of the velocity vector so as to discretely change the flight path angle of the vehicle. This task investigates the use of flight path angle changes to control the trajectory of the vehicle so that the terminal constraints are satisfied.

This method of control was proposed by Hedge, Ref. 2. He introduced an unbounded control of the flight path angle using a first order sensitivity equation to solve for the magnitude and direction of the flight path angle change required. After a discrete change of the ballistic coefficient at the entry altitude, 89,400 ft. above the Martian surface, the first order sensitivity equation was used to estimate the terminal range error and calculate the needed control, i.e., the change of flight path angle. The control calculated by the first order sensitivity equation is referred to as the unbounded control. However, the first order sensitivity equation provides a poor approximation of the terminal range error. In other words, it gives a very inaccurate indication of the change of flight path angle required to correct the trajectory so as to reduce terminal range error. Therefore, the values of unbounded control which are calculated by the first order sensitivity equation tends to overcorrect the trajectory. Moreover, a large amount of fuel, about 310 lbs. for a chemical rocket, is used for this purpose. This is not very economical when only half of the range error is eliminated compared to the uncontrolled case. Thus a better scheme needs to be found which will not only reduce the terminal range error by a great amount but also will reduce the cost of fuel during the flight.

The unbounded control has a tendency to push the trajectory too far. If the magnitude of the change of flight path angle can be bounded to reduce the overcorrection, it should be possible to reduce the terminal error while using less fuel. In this case, the first order sensitivity equation is not used directly in the calculation of the bounded controls. Instead, the polarity of the estimated final range error is used to indicate the direction of the control. Therefore, the inaccuracy of the first order sensitivity equation will not effect the bounded scheme as much as in the unbounded case. By using four discrete changes of flight path angle and VM8 as the reference atmospheric model, if a VM4 model is assumed as the actual atmosphere, a most suitable bound for the control can be found at $\Delta\theta_c(s) = 0.001$ rad. which reduces the terminal error about 15 times more than the unbounded control and 30 times more than the uncontrolled case as can be seen in Table 1. The comparison of cost of fuel and terminal velocity is also shown in Table 1. The fuel required for the best bound of control is only 5.65 lbs. which is about 55 times less than the unbounded control.

The advantages and disadvantages of best bounded control can be concluded as follows:

(1) The best bounded control reduces the terminal range error considerably.

(2) The best bounded control uses much less fuel than the unbounded control. This is a very important advantage especially if it is desired to have the vehicle return from the Martian surface. Under this condition, the fuel constraint becomes the most important in the control problem.

(3) The terminal velocity of the vehicle is also smaller than in the unbounded case. However,

since both are far below the required value of 1,000 fps. this is not as important as (1) and (2) above.

(4) The only disadvantage of the best bounded control is that it is hard to implement on an on-board computer in the vehicle since the parameters of the actual atmospheric model have to be updated as the vehicle flies through the martian atmosphere and the best bound of control is not apriori known. However, since the first atmospheric dependent correction will not be made an altitude of 76,000 ft., is reached updated parameters can be made available. Hence, a best value for the control bound can be found according to the updated values at 76,000 ft. As more accurate parameter updates are obtained a new best bound for the control can be calculated which should be in the neighborhood of the first value if the parameters are nearly the same. Although this scheme will require longer computing time, the advantages of reduced fuel penalty and smaller terminal range error support the conclusion that the best bounded control is superior to the unbounded control. Furthermore, if the updated atmospheric parameters converge very rapidly to fixed values, then the best bounded control scheme would be optimal for this problem because fixed values are easy to program into the computer for use in calculating the correction at next altitude.

TABLE I

Reference Atmospheric Model	VM8
Assumed Actual Atmospheric Model	VM4
Terminal Altitude	20,000 ft.

	Terminal Range Error (rad.)	Cost of Fuel (lbs.)	Terminal Velocity (fps.)
Uncontrolled	-0.592×10^{-4}	0	522
Unbounded Control	$+0.294 \times 10^{-4}$	310	562
Best Bounded Control	-0.017×10^{-4}	5.65	518

Task B. Unpowered Aerodynamic Landing - T. Kershaw
Faculty Advisor: Prof. G.N. Sandor

It has been proposed that the unpowered rotary wing is capable of providing the best aerodynamic means of controlled deceleration and touchdown for unmanned instrument packages in planetary exploration. The objectives of this task were:

(1) to develop the mechanical design of the unpowered rotor in sufficient depth to provide realistic weight and strength limitations;

(2) to develop a theoretical aerodynamic analysis for the mechanical design describing the operational characteristics of the rotor;

(3) to make a detailed comparison between the efficiency of the unpowered rotor concept and methods for controlled descent presently being used.

Predictions of rotor performance as obtained from the closed form analysis and the computer solutions were found to be in disagreement. A review of the closed form analysis disclosed several minor errors which have been corrected so that consistant results are now being obtained.

Further progress has been delayed by recent systems modifications in the central computing facilities. These modifications require some adjustments in the computing program before additional study can be undertaken.

During the coming period, it is intended that the computing programs be modified to permit their use and that the necessary calculations be made to permit for a comparison between the autogyro concept and more conventional landing schemes to be made.

Task C. Terrain Modeling, Path Selection and Navigation

The mission plan to undertake a systematic exploration of Mars requires that the roving vehicle can be instructed to proceed under remote control from its landing site to a succession of desired locations. This objective requires that the vehicle possess the capabilities: of sensing and interpreting the terrain to provide the information required by a path selection system, of selecting paths with due regard to safety and other considerations, and of knowing its location and that of its destinations. Tasks relating to these objectives have been defined and are under active study. The progress achieved to date is described in the sections immediately following.

Task C.1.a. Terrain Modeling - Carl Pavarini
Faculty Advisor: Prof. D.K. Frederick

It is intended to supply the Martian roving vehicle with the capability to choose autonomously the path it will travel once given a target destination. To accomplish this task, it will be necessary to first model the terrain, and then create an algorithm which will utilize this information to pick an obstacle-free path which will hopefully also minimize other cost factors.

This portion of the study is concerned with the problems related to the task of terrain modeling. It is desired to generate a model of the terrain ahead of the vehicle from measurements obtained by a discrete, line-of-sight, electromagnetic sensor. For the purpose of this study it has been assumed that there is an ideal sensor, i.e., one which is errorless in determination of range and has zero beam-width. By pointing the sensor, e.g., radar, in a specified direction, the range (R) to the terrain may be measured as a function of the two independent variables azimuth angle (α) and elevation angle (β). It has been assumed that the sensor will scan to take data at discrete values of β for a constant azimuth angle. Because the interest is in long-range paths, the ranges of interest are those exceeding 200 ft.

The terrain modeling analysis breaks down into two separate but related problems: terrain data acquisition and processing.

Data Acquisition

Enough information about the terrain must be obtained so that it can be said that the terrain is "defined". To put this concept in quantitative terms, if a difference of more than 300 ft. between adjacent range readings is encountered, it is said that the region is "undefined".

Thus, the problem of data acquisition is not only to obtain data to allow identification of obstacle features, but to have enough data to be able to predict the absence of obstacles.

It was decided to utilize a single sensor at a fixed height (which, for the purpose of increasing the angles of incidence between the beam and terrain, should be as high as possible). A sensor height of ten feet was chosen for the purposes of simulation. The azimuth angle increment was set at five degrees, and the elevation angle increment at five milliradians, with with provisions for reducing this increment to 5/3 milliradians if the interval between measured ranges exceeds 300 ft.

The sensor is assumed to scan vertically at increasing elevation angles beginning at that angle for which the range is approximately 200 ft. A primary scan is done with $\Delta\beta = 5$ mr. If the measurements indicate the presence of an undefined region starting at $\beta = \beta_o$ then $\Delta\beta$ is reduced to 5/3 mr for all $\beta > \beta_o$, for that azimuth angle.

Computer simulations were carried out for individual two-dimensional terrain profiles to guide the selection of the parameter values used. Of course, any choices will be constrained by practical considerations (ideally, the sensor height would be as large as possible and would approach zero).

The conclusion drawn from this analysis is that it was much easier to define radically varying terrain than the type of terrain one would hope the vehicle would normally travel (flat or gently sloping). In most cases, it was necessary to use the small elevation angle to "define" the terrain. In addition, the use of the smaller increment does not always improve terrain definition, the extreme case being that in which parts of the terrain were hidden from view.

Data Processing for Model Generation

The model generated by the system will hopefully give the range-to-obstacle along each azimuth line in question. However, it is necessary to distinguish between the following classes of obstacles:

1. In-path slope - where the slope of the line connecting two consecutive data points along an azimuth line exceeds a predetermined maximum, Figure 1.

2. Cross-path slope - where the slope of the line joining two data points of approximately equal range on adjacent azimuth lines exceeds a predetermined maximum, Figure 2.

3. Unknown region - where, after utilization of the smallest $\Delta\beta$ available for a scan along an azimuth line, there are points separated by more than a predetermined distance.

4. Out-of-range - where, after finding none of the three previous obstacles along an azimuth line, an increase in elevation angle results in no reasonable range measurement (say less than 5000 ft.). In this sense, all lines will show an obstacle, for there will always be some range beyond which there will be no available data.

Simulation Results

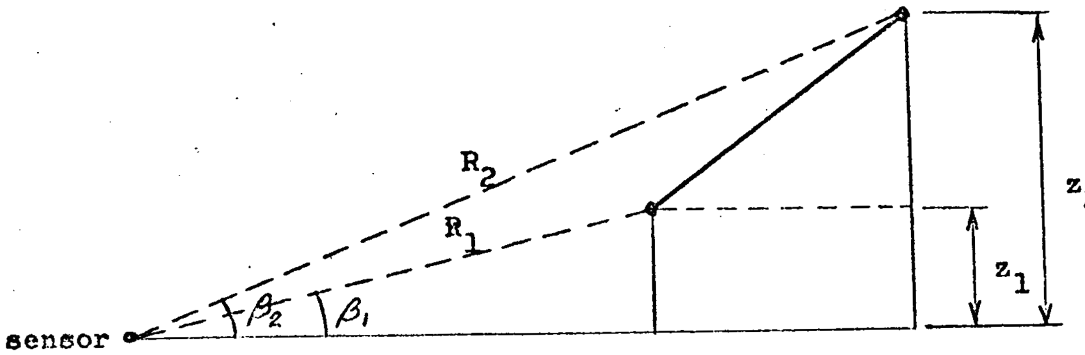
A three-dimensional terrain segment defined over a 60° pie-slice shape with a 3000 ft. radius was chosen according to the following criteria:

1. agreement with the most recently published studies of the Martian surface (Ref. 3) as to typical obstacles.

2. knowledge gained from previous data-acquisition analysis as to what types and dimension terrain features would be most likely to present challenges to the system.

Keeping in mind the fact that results may be highly dependent upon the actual terrain used, the following conclusions can be stated:

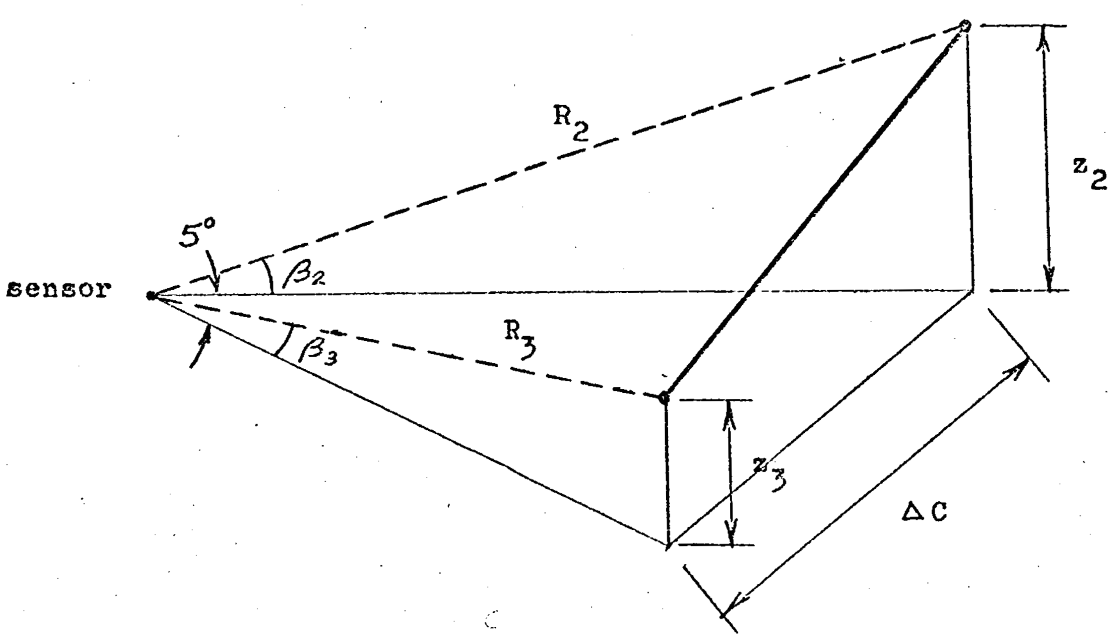
1. In-path obstacles can be detected with little error.



$$z_i = \beta_i R_i$$
$$z = z_{i+1} - z_i$$
$$R = R_{i+1} - R_i$$

$$S_I = \frac{\Delta z}{\Delta R}$$

FIGURE 1: In-Path Slope Determination



$$\Delta C^2 \doteq R_2^2 + R_3^2 - 2R_2R_3 \cos 5^\circ$$

$$S_c = \frac{\Delta z}{\Delta C}$$

FIGURE 2: Cross-Slope Determination

2. It is extremely difficult to accurately detect the presence of a cross-path obstacle and the method used in this study is unsatisfactory, (this was due to the dependence of the present scheme upon a "good match" between points on adjacent azimuths).

3. Unknown-region obstacles are a very real problem due to the frequency of their occurrence.

4. A terrain which is easily defined along a particular azimuth tends to be defined for only a relatively short distance from the sensor, beyond which little or no information can be gathered.

5. Adequate definition of difficult-to-define terrains does not seem possible for ranges beyond some intermediate value (say 1500 to 2000 ft.).

Proposed Study

Continuing work is proposed in the terrain modeling area to resolve the problems incurred in the simulation. It seems necessary to forego the simplicity of delineating in-path and cross-path obstacles, such as formulating a method of calculating the gradient of the plane determined by three points. In this way, it is hoped to overcome the problems in determining slope obstacles encountered with the two-point method. One simple method already exists for which simulation has been accomplished (Ref. 4) and another has been recently developed by the author. It is proposed to utilize these methods on the terrain modeling simulation performed previously and determine the quality of the results as opposed to the past results as well as an "ideal" solution. The conclusions that will be drawn from this work should result in an appraisal of what can be accomplished in the area of terrain modeling at the expense of increased data processing complexity.

Assuming that the planar slope method yields improved results, the terrain modeling system will generate values of the range-to-obstacle for each asimuth value, along with an indication of the types of obstacles - excessive gradient, unknown region, or out-of-range. As further work on a completely automatic roving capability will necessitate the formulation of a path-selection algorithm, study will have to be done to determine a method or methods of comparison for the various proposed algorithms.

The basis for comparison will be partially dependent upon the information available about the terrain (the type and quality of the terrain model). It is hoped to phase the terrain modeling work into the path-selection effort within the next month.

Task C.1.b. Evaluation of Automatic Path Selection Algorithms - J. Chrysler
Faculty Advisor: Prof. D.K. Frederick

The three basic steps in the ground navigation system are data acquisition, terrain modeling, and automatic path selection. Past work in the area of automatic path selection has primarily been concerned with the formulation of various path selection algorithms. Because it is possible to devise a great variety of path selection algorithms, it becomes important to have a measure by which different algorithms may be compared. The objectives of the task are: (a) To devise a method for quantitatively evaluating path selection algorithms, (b) To evaluate existing path selection algorithms.

Plans call for developing a performance index, or set of indexes, that will assign a quantitative measure to the performance of a path selection algorithm. To do this, it will be necessary to ascertain those parameters of the overall system which are most important and, in particular, to determine those features of the vehicle's design which might affect the evaluation process.

Aside from the evaluation of algorithms, the formulation and study of performance indexes should provide valuable insight into how to devise a "better" path selection algorithm to meet certain needs.

The first problem is to decide what types of information a performance index should include. Areas that would appear to be of primary concern are: safety and success in finding a path; power and energy requirements for driving the vehicle; and computational requirements.

Safety and Success in Finding a Path

Success in finding a path and the safety of that path are closely related subjects and are both quite important. However, in a mission of this type, the safety of the vehicle would be of the utmost importance. For instance, it would be far more desirable to fail to find a path to a desired destination and to retain the safety of the vehicle rather than to loose the vehicle in an attempt to negotiate an unsafe path. It is because of this high priority on the safety of the vehicle that a performance index dealing with the safety of a path generated by an algorithm was the first to be investigated. This index is discussed briefly below.

Power and Energy Requirements

The power and energy requirements for the operation of the vehicle constitute another area of great importance. Although the length of the path is an obvious and important factor, the physical make up of the vehicle and its energy requirements will also affect the way in which path selection algorithms should be evaluated. Whether or not the vehicle has a regenerative power supply system would definitely effect the acceptability of a flat path compared to one that climbs and descends a number of slopes. An important question in this area is whether or not the two dimensional terrain model which is presently being studied contains enough information for proper path selection. It is conceivable that the energy required for steering the vehicle could also affect the evaluation of a path.

Just how these and other energy considerations affect the algorithm evaluation process and how an index relating to them might be devised will be the subject of study in the immediate future.

A Performance Index for Path Safety

The fundamentals of an Average Safety Index (A.D.I.) have been formulated. On a sample obstacle configuration, representing a two dimensional terrain model, regions are drawn about the obstacle and assigned a danger level. The danger level would naturally increase as an obstacle is approached. Given the path generated by a path selection algorithm, an average danger index is computed according to the following formula:

$$\text{A.D.I.} = \frac{\sum_{\text{all regions}} (\text{danger level})^2 \times (\text{length of path})}{\text{total length of path}}$$

Figure 3 shows an example of how this index might work, using a 0 to 10 danger level scale. The results of this example agree with the intuitive feeling that path 2 would indeed be a safer, and better, path than path 1.

Squaring of the danger level in the formula gives a greater penalty for crossing from an 8 to a 10 region than from a 2 to a 4 region. If a linear relationship was used, it would result in a uniform penalty throughout the range for crossing into a higher danger region. The squaring is consistent with the high concern for safety and should give a wider spread in the index values calculated for various algorithms.

More work needs to be done on this index to determine what obstacle configurations should be used and just how to draw the danger regions in order to get the best results.

Four path selection algorithms are available for the testing of various performance indices and as an aid in formulating new indices. To present, the majority of the effort has been devoted to getting the computer programs simulating these algorithms operational and in modifying them to accept the same type of input data.

The preliminary criteria presented above will be further refined and methods of expressing them quantitatively will be examined. It is expected that computer simulation using the existing selection algorithms will play an important role.

Task C.2. Navigation Systems

Task C.2.a. Primary Navigational System for a Martian Roving Vehicle - Ronald E. Janosko
Faculty Advisor: Prof. C.N. Shen

The navigational scheme must be able to locate destinations that the vehicle might want to explore with respect to a coordinate system in the vehicle. Many navigation schemes and algorithms have been devised to get a roving vehicle around objects and to a destination, Ref. 5. Basic to all of these schemes is the fact that the vehicle knows where the destination is. The objective of this task is to develop a primary navigation scheme which will allow the vehicle to locate itself and its destination in some coordinate system.

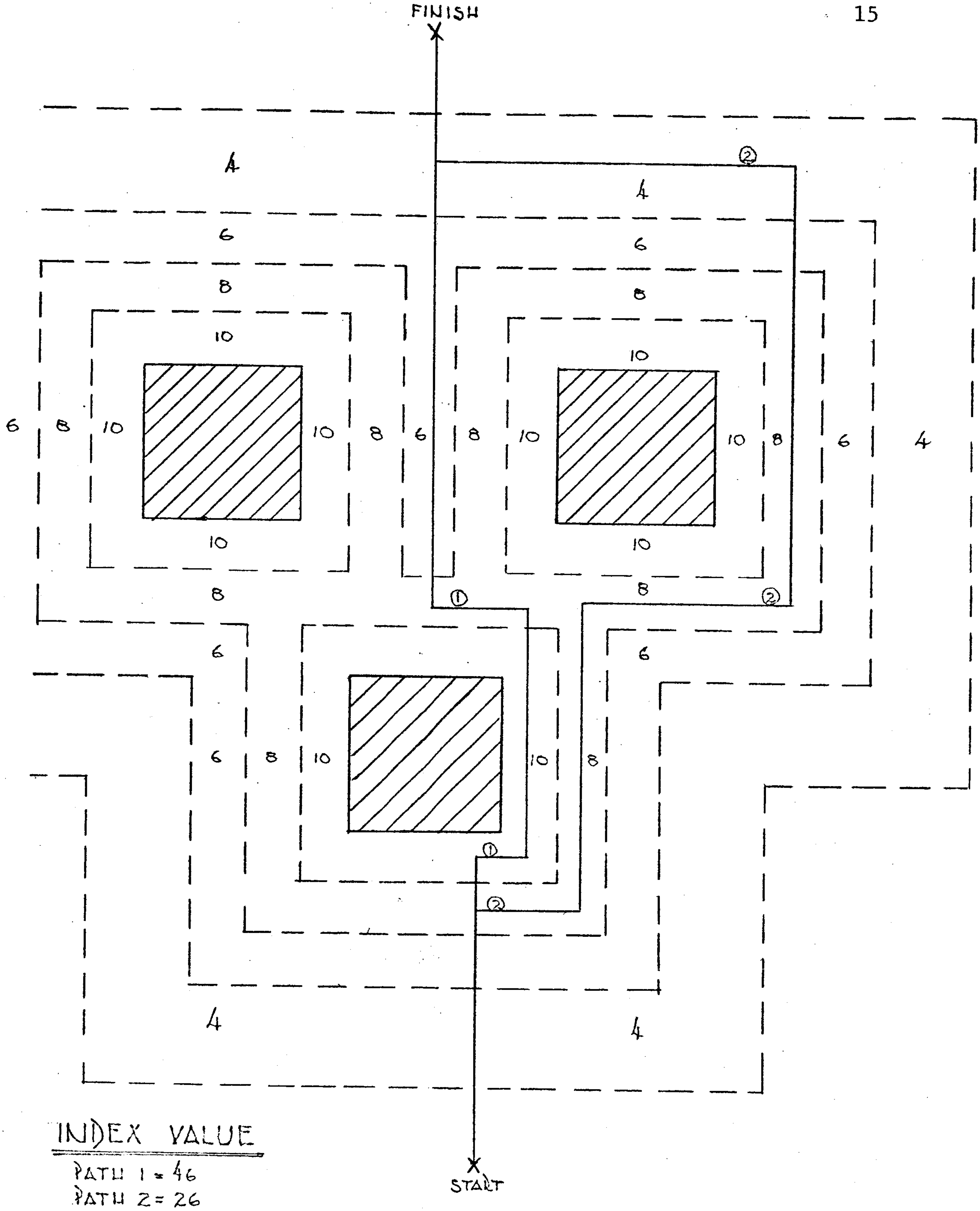


FIGURE 3: Example of the Use of the Danger Index

At first this seems to be an easy task. The vehicle needs only to look about its landing sight until it finds a predetermined target. The problem with this simple sounding scheme is that most likely the vehicle will land near a target but in order to get maximum use out of the roving vehicle it would be best for the vehicle to explore another more distant target. Here is where the problem arises. If the next target is quite distant, say over fifty miles away, there is a good possibility that some physical surface feature will obstruct direct observation of the target by the vehicle. We note immediately that a primary navigational system must be effective even if obstacles block direct observation of the target. The observation range is also limited by the curvature of the Martian surface. One alternative to increase the range of observability is to include the orbiter in the system.

The scheme under investigation uses the orbiter to observe the lankmark in its own reference frame. In turn the orbiter is observed by the vehicle in a vehicle frame.

The basic scheme, Ref. 6, involves orbiter sighting of the landmark and vehicle sighting of the orbiter at two successive sighting times.

Figure 4 shows the situation. In this figure C is the planet center, L and V are the lankmark and vehicle respectively. P^1 and P^2 denote the position of the orbiter at the two sighting times. The x_1, x_2, and x_3 coordinate system is located on the vehicle and all vehicle measurements are made with respect to this system. The y_1, y_2, and y_3 coordinate system is on the orbiter and all orbiter measurements are made with respect to this system. Note that it is assumed that the y system is only translated as the orbiter travels from P^1 to P^2 and that there are no rotations with respect to inertial space. The coordinate system centered in the planet is merely to aid in the representation of the figure.

For this navigation concept to function properly the vehicle needs to be able to measure:

1. The vector $\overline{VP}^1$ and $\overline{VP}^2$

2. The unit vector $\hat{VC}$

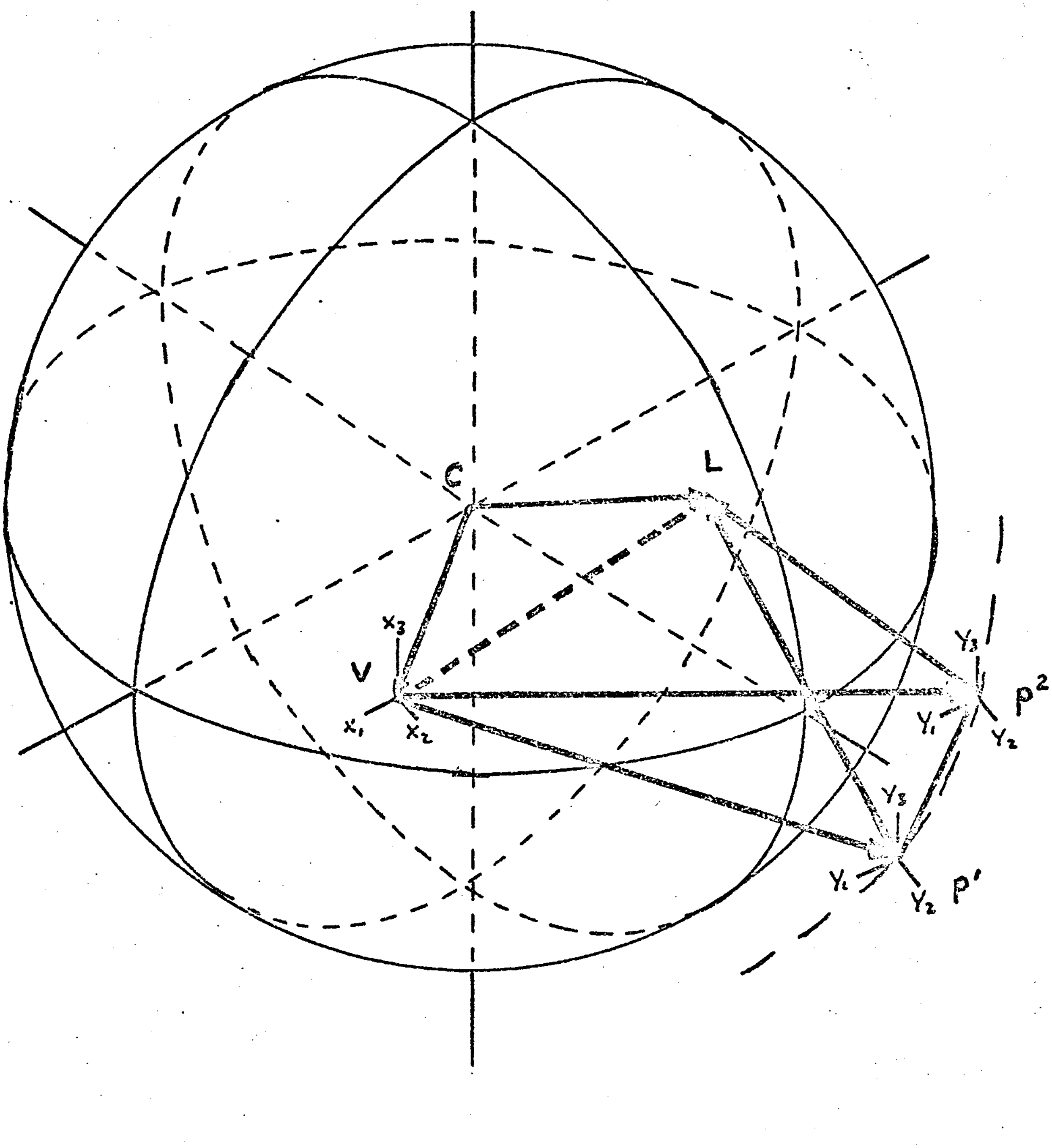


FIGURE 4: Conceptual Navigation Systems

The orbiter has to be able to measure:

1. The unit vectors $\widehat{P^1L}$ and $\widehat{P^2L}$
2. The unit vector $\widehat{P^1C}$ and $\widehat{P^2C}$
3. The height above the planet's surface at the times t_1 and t_2.

It is assumed that the first set of measurements involving P^1 are made at t_1 and likewise those involving P^2 are made at t_2. Geometric and trigometric relationships are then used to construct a common reference frame, and also to determine the desired VL vector.

An initial attempt at a geometric system failed because it could not accommodate measurement errors. By this it is meant that the scheme's equations could not be manipulated to provide a filtering of the measurement noise. By reformulating the problem as a state estimation problem, errors could be properly incorporated for filtering.

The state parameters to be estimated are the latitude angle, longitude angle and radius to the rover and landmark, (see Figure 5). From these parameters the navigation vector can be found.

The main result to date has been the reformulation of the problem as a state estimation problem in order to obtain meaningful results. As previously stated the initial approach did not allow for a convergence scheme as would be necessary for most filtering solutions.

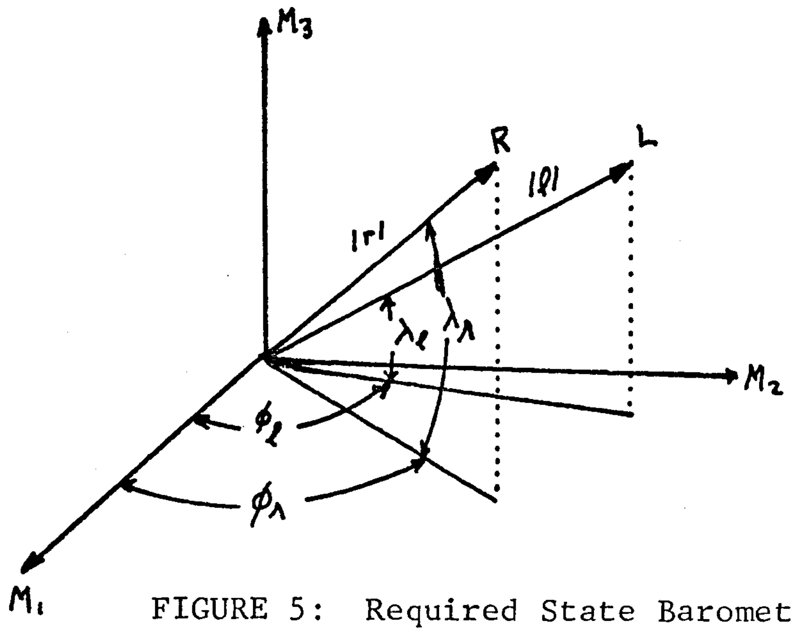


FIGURE 5: Required State Barometer

$|r|$ = radius to rover

$|l|$ = radius to landmark

λ_l = Landmark latitude angle

λ_r = Rover latitude angle

ϕ_l = Landmark longitude angle

ϕ_r = Rover longitude angle

M_1, M_2, M_3 = Mars geographic reference frame.

This is because under this representation the only constant is the landmark. In the reformulated problem all parameters can be treated as constants and an additional scheme is used to update the vehicle parameters as it moves along the Martian surface.

Future research on this task will call for an extensive study available methods that might be used to solve the filtering problem. If an available method is applicable then it must be implemented and tested. If no method is available, a new method will have to be developed and implemented.

Task C.2.b. <u>Reference Coordinate System for Surface Navigation</u> - Larry Hedge
Faculty Advisor: Prof. C.N. Shen

Task C.2.a. described a navigation scheme using the orbiters to determine the position of a surface roving vehicle. Through the use of discrete sets of measurements, a statistical fit is performed to recursively determine the rover's position on the surface, Ref. 6. However, since the estimation process is time consuming, it would be desirable to allow the vehicle to move between the old and the new, updated estimate of position. Therefore, it has been the purpose of this task to design a scheme that will allow roving vehicle to maintain a knowledge of its present position by tracking its movements from a given starting point. Such a system may also be used to maintain an estimate of the rover's position where the orbiter is out of sight of the rover.

The objective is to describe the position of the rover with respect to a coordinate system fixed in the planet as the vehicle moves along the surface from some given initial point. The navigation scheme must use measurements (distance, velocity, or acceleration) made with respect to a coordinate system in the rover, and must account for the time relationship between the rover's frame and the planet-fixed frame.

The concept of an inertial platform in the rover was set aside in order to investigate the use and feasibility of a moving, non-inertial reference frames. It was felt that it might be possible to achieve a system significantly lighter than an inertial platform by adopting a moving frame and that the only penalty incurred would be a small increase in the amount of onboard computation required.

A coordinate system was chosen which uses an alignment technique similar to one used on Earth for hundreds of years. The first axis, x_1, (see Figure 6) is pointed in the direction of a pole star of Mars. This establishes one of the coordinate axes parallel to the spin axis of Mars, a fact which becomes very useful in the description of the tracking system. The second coordinate direction, x_2, is established by measuring the direction of local vertical. The x_3 vector and the local vertical vector then defines a plane of longitude on the planet. The perpendicular to this plane in an eastward direction is to be taken as the x_2 direction. The third axis, x_1, is the cross product of x_2 and x_3. An advantage of this system is that the relationship of this frame to the planet-fixed Mars frame is only a function of the rover's position on the surface. The x_1 x_2 plane is always parallel to the equatorial plane of Mars and therefore the coordinate system only rotates about the x_3 axis. Also the rotation can only occur if the vehicle moves with respect to the surface.

The problem is now to develop a scheme which uses measurements in the rover's x-frame to determine the vehicle position relative to a given starting point.

The geometry for the tracking system is shown in Figure 6. The transformation of a vector in the x-frame (rover) to the M-frame (planet-fixed) at any time can be expressed by using a transformation matrix $T(t)$.

Now consider measuring the rover's velocity with respect to the surface. Instantaneous velocity can be expressed exactly as a vector quantity in the x-frame and there exists a specific value of $T(t)$ for this vector. Since the value of $T(t)$ is only dependent on the vehicle's position, it is possible to transform the measured velocity to the M-frame.

A mathematical description of the position tracking system allows for the location of the vehicle by continuous measurement of its surface velocity in its own non-inertial frame. The rover's reference frame rotates with respect to a planet-fixed frame only when the vehicle moves across lines of longitude. A set of differential equations were derived which when solved yield a time relationship between the rover's velocity with respect to the surface and the rover's position on the surface.

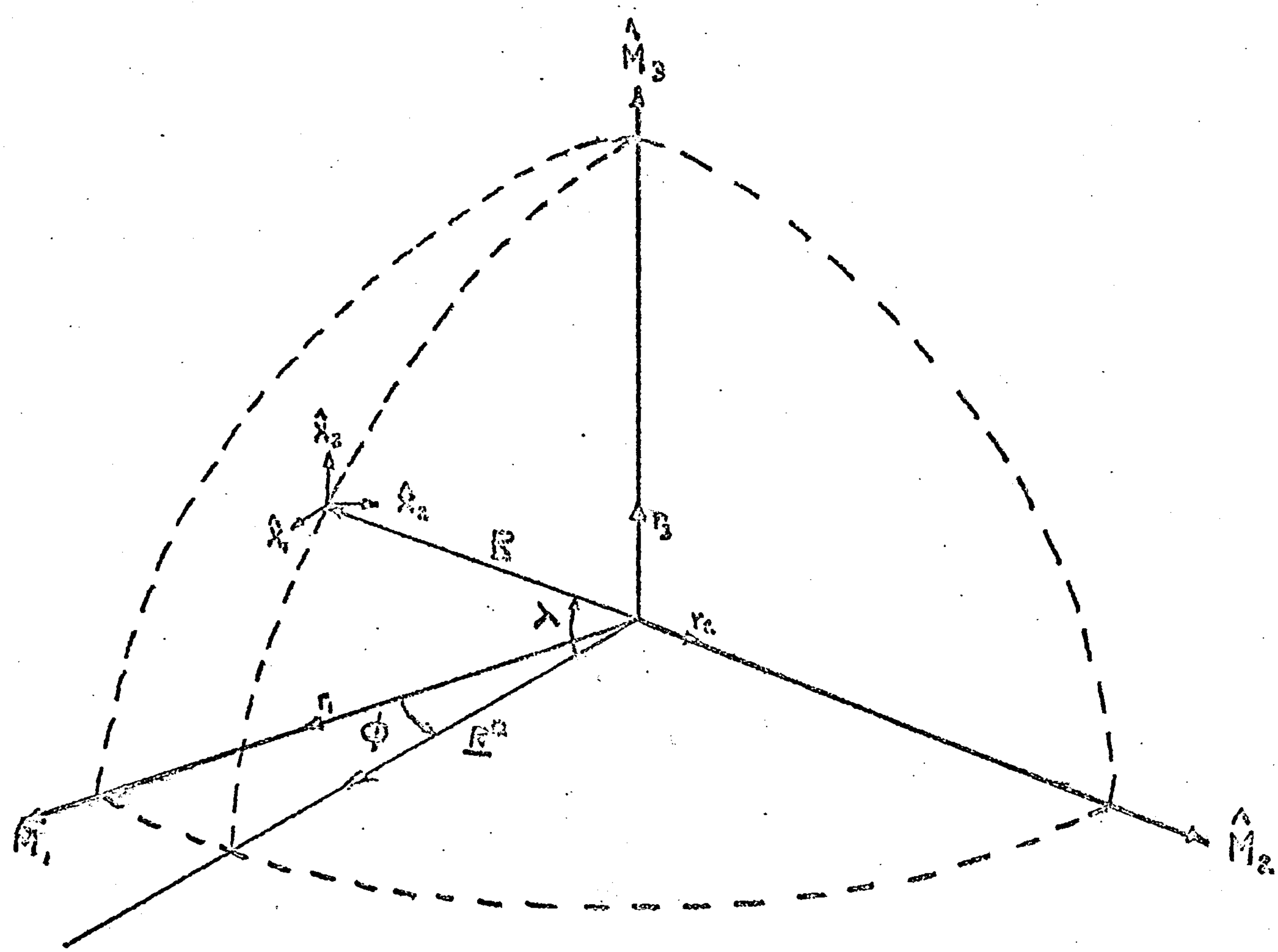


FIGURE 6: Geometry of Proposed Tracking System

The set of differential equations is non-linear. However, due to the specific choice of the vehicle's reference coordinate system and its relationship to a coordinate system fixed in the planet, the equations are concise. Since the vehicle will be moving at very low speeds, digital integration techniques should prove effective and very rapid in obtaining the solutions to the differential equations.

Work is underway to determine the feasibility of such a coordinate system. Conclusions reached at this point are that given the existence of such a coordinate system, the position of the rover can be tracked within the accuracy of the given initial starting point. The feasibility of establishing such a frame, or one similar, remains a prime task objective.

Task C.2.c. Instrumentation for Navigation System -
J.V. Wilson
Faculty Advisor: Prof. C.N. Shen

The objective of this task is to investigate systems of instrumentation for the navigation system concept described under Task C.2.a. with the purpose of determining the implications which the required hardware might have on the feasibility of the basic system. Since this primary navigation system for an unmanned-roving vehicle was quite different from conventional systems, there appeared to be considerable opportunity for investigation of new types of instrumentation, new coordinate frames, and new schemes of calculations for solving the basic navigation problem. It was in fact discovered that several new frames might be of interest, and that several rather unusual sensing devices might have to be developed to properly utilize this system. In fact, the results of this study combined with error analysis of the basic system, Task C.2.a., have lead to a major revision of the basic system itself, which will now require still further instrumentation study.

The initial effort in the study was designed to establish the general environment in which the sensors would operate, determine the quantities which would have to be measured, and define a set of general requirements which all instruments would have to meet. This would include such items as weight, power, accuracy, reliability, etc. The second effort was a study of existing instruments which might possibly be matched to the individual jobs to be done. Basically, the measurements required by the system were as follows:

a. Vehicle: local vertical
satellite range and bearing

b. Satellite: local vertical
satellite altitude above the Martian surface
direction of Martian surface landmark from satellite

It was found that direct sensing of local vertical in a dynamic environment from both the satellite and the vehicle were very difficult problems, and that the satellite tracking of the landmark was also extremely difficult. The local vertical problem can forseeably be overcome by determining local vertical for the satellite from a knowledge of the orbit parameters, and for the vehicle by having the satellite track the vehicle and compute the vehicle's local vertical for it. The tracking of a non-radiating surface landmark is still not solved.

The two major vehicle reference frames which were considered in conjunction with Task C.2.b., were a pole star/local vertical frame and a sun/local vertical frame. The pole star frame was very interesting because of its computational simplicity and light weight instrumentation, along with the fact that it could be maintained day or night as the planet rotated. Unfortunately, it has definite geographic limitations. It cannot be used at all in the northern hemisphere, (there is only a southern pole star, no northern), nor near the equator, (because of visibility restrictions near the horizon), nor close to the south pole, (because of the singularity there between the local vertical and the pole star axis). This leaves only the southern mid-latitudes. The sun frame is instrumentationally superior because the sun is even easier to track than the pole star, but it is computationally quite complex. The relationship between the sun frame and the Martian geographic frame is not a simple rotation as for the pole star frame. Its geographic limitations, although different from those of the pole star frame, are still quite real. The sun frame can be used anywhere on the planet, but only for certain periods of the year and/or for only certain times of the day. For example, the frame is excellent at the poles, where the sun and local vertical are nearly at right angles all day, but this is only true for the summer months since the sun is not visible at all in winter. Near the equator, care must be taken to avoid the singularity of having the sun pass nearly overhead, and of course the sun passes out of sight each evening. Again, this leaves the mid-latitudes as the only favorable area if the mission is to last a full year.

The difficulties in instrumenting the system lie primarily in the tracking of the surface landmark by the orbiter and in selection of a coordinate frame to cover all, or at least most situations. The project has thus far been kept quite flexible and has studied the possibilities of instrumenting many kinds of systems in various environments at the expense of detailed work on any one system. It is considered that this has been beneficial because it has produced several new and interesting ideas with several more possibilities yet to be investigated, but it is in general difficult to make any decisions or evaluations without more detailed feedback on mission goals.

It is expected that the work for the coming period will be devoted to further work on the landmark tracking problem, the calculations required for local vertical determination, and the implications of the new navigation system proposed under Task C.2.a. to limit the investigation somewhat to permit a deeper study of a smaller number of details. Limitations will be made on the basis of whatever refinements are made in the mission requirements by cognizant personnel and other assumptions will be made by project personnel as necessary to allow the work to proceed.

Task C.3. Self-Contained Navigation Systems - A.L. Goldberg and P.J. Frankel
Faculty Advisor: Prof. E.J. Smith

The objective of this task is to design a navigation system for a roving vehicle using body-bound gyroscopes. The system must be capable of sensing vehicle attitude giving pitch, roll, and yaw and/or Euler angles of the craft with respect of its original landing position, which is assumed known. It was desired that two types of systems be considered; one using single-degree-of-freedom gyroscopes and one using two-degrees-of-freedom gyroscopes.

The first system to be investigated was that using two-degrees-of-freedom gyros. A "practical" proof of the derivation of the attitude matrices has been presented in Ref. 8 using a qualitative procedure. From this, it was discovered that a system using three two-degrees-of-freedom gyroscopes was physically unrealizable. The reason for this can be easily seen by examining Figure 7. If a third gyro of $\theta_o = 90^o$ and $\psi_o = 90^o$ would have to be imposed on its gimbals. This would cause the gyro to cease functioning as a two-axis sensing device. Therefore, the only configuration that satisfies the criteria of Ref. 7 is that shown in the Figure 7. It was then essential to show that the angle transformation matrix for the three two-degrees-of-freedom gyros yielded idential results to the angle transformation matrix using two two-degrees-of-freedom gyros. This requirement has been met.

Subsequently, attention was turned to the single-degree-of-freedom gyro system and an effort made to derive the corresponding attitude matrix. This was done to ascertain at an early stage whether either system would have significant advantages over the other so as to make further investigation into the latter unnecessary. An extensive literature search revealed that the outputs of a system using single-degree-of-freedom gyros cannot be used to uniquely define the orientation of a vehicle. As a result, a hybrid system was chosen as an alternative. Figure 8 shows such a system in its equilibrium position. Upon rotating the craft by an angle   about the z-axis, Gimbal orientations similar to those shown in Figure 9 result. Displacement caused by a rotation about a gyros output axis yields a "true" angle ("true" being Eulerian) measurement by that gyro (θ_2 , Figure 9). On the other hand, any rotation about a gyros' input axis will produce a signal that will cause the gimbal on this gyro to experience zero net deflection (i.e. a torque on the gimbal of gyro no. 3 in Figure 9 to make $\theta_3 = 0$). Due to numerous forseeable problems, this system was tabled and work resumed on the dynamics of the two-degrees-of-freedom gyro system.

Presently under investigation are the dynamics of the two-degrees-of-freedom system. The primary method being developed is based upon work reported in Ref. 9.

Future plans include completion of the analysis of both system types and a comparison of the two with respect to vital system parameters and integration of the system into the overall vehicle design.

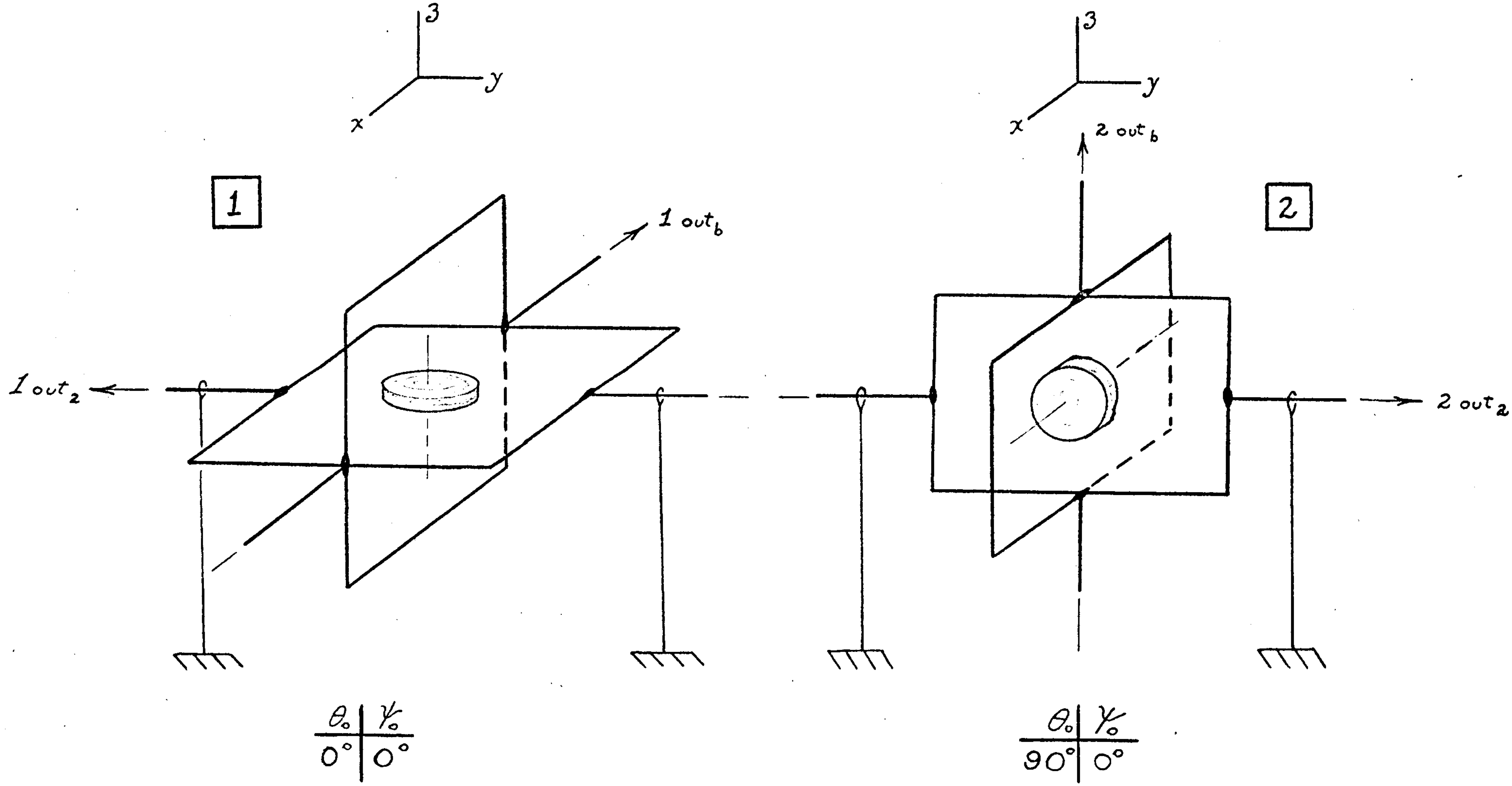


FIGURE 7: Two-Degree-of-Freedom Gyroscope Orientation

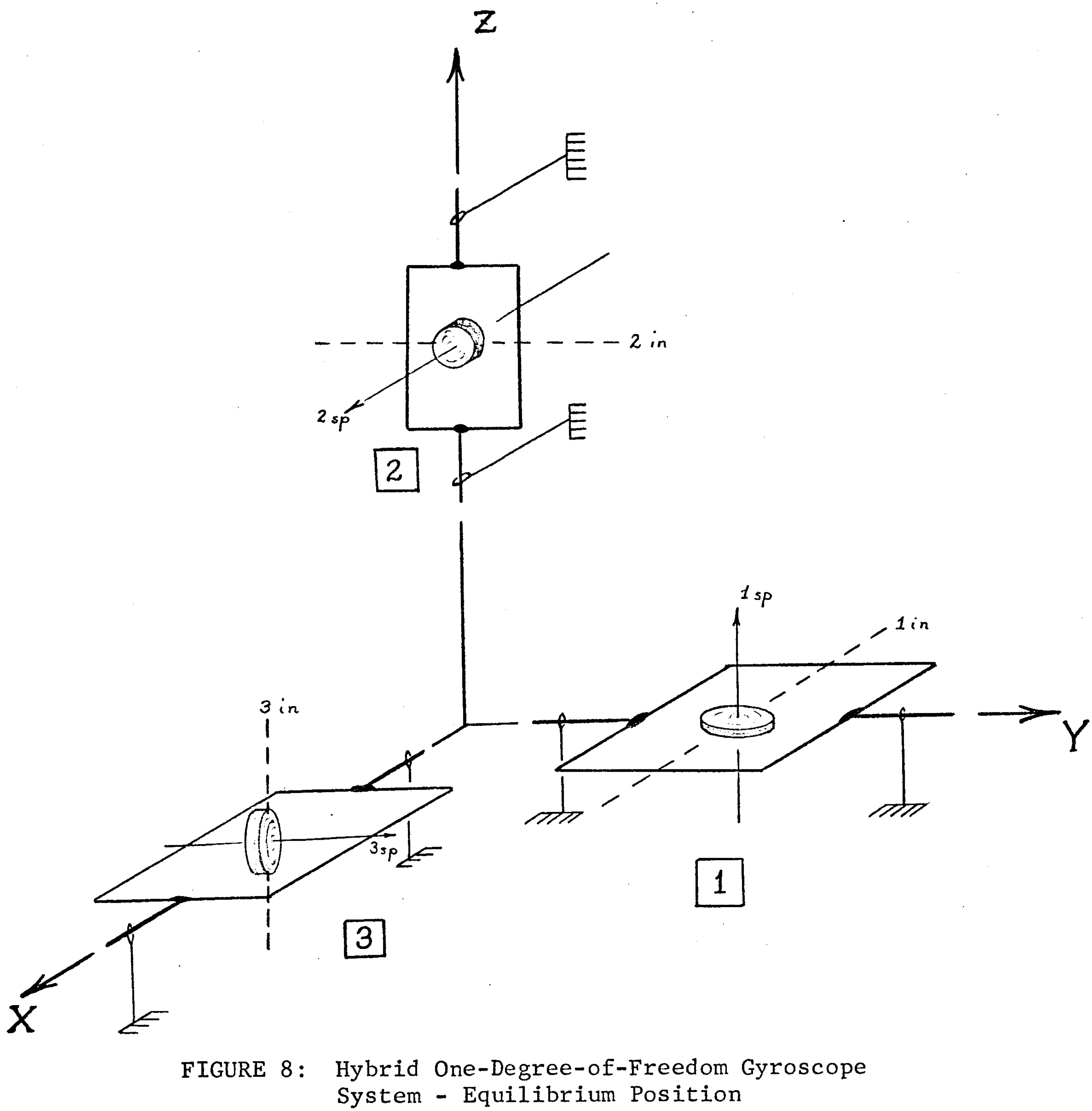


FIGURE 8: Hybrid One-Degree-of-Freedom Gyroscope System - Equilibrium Position

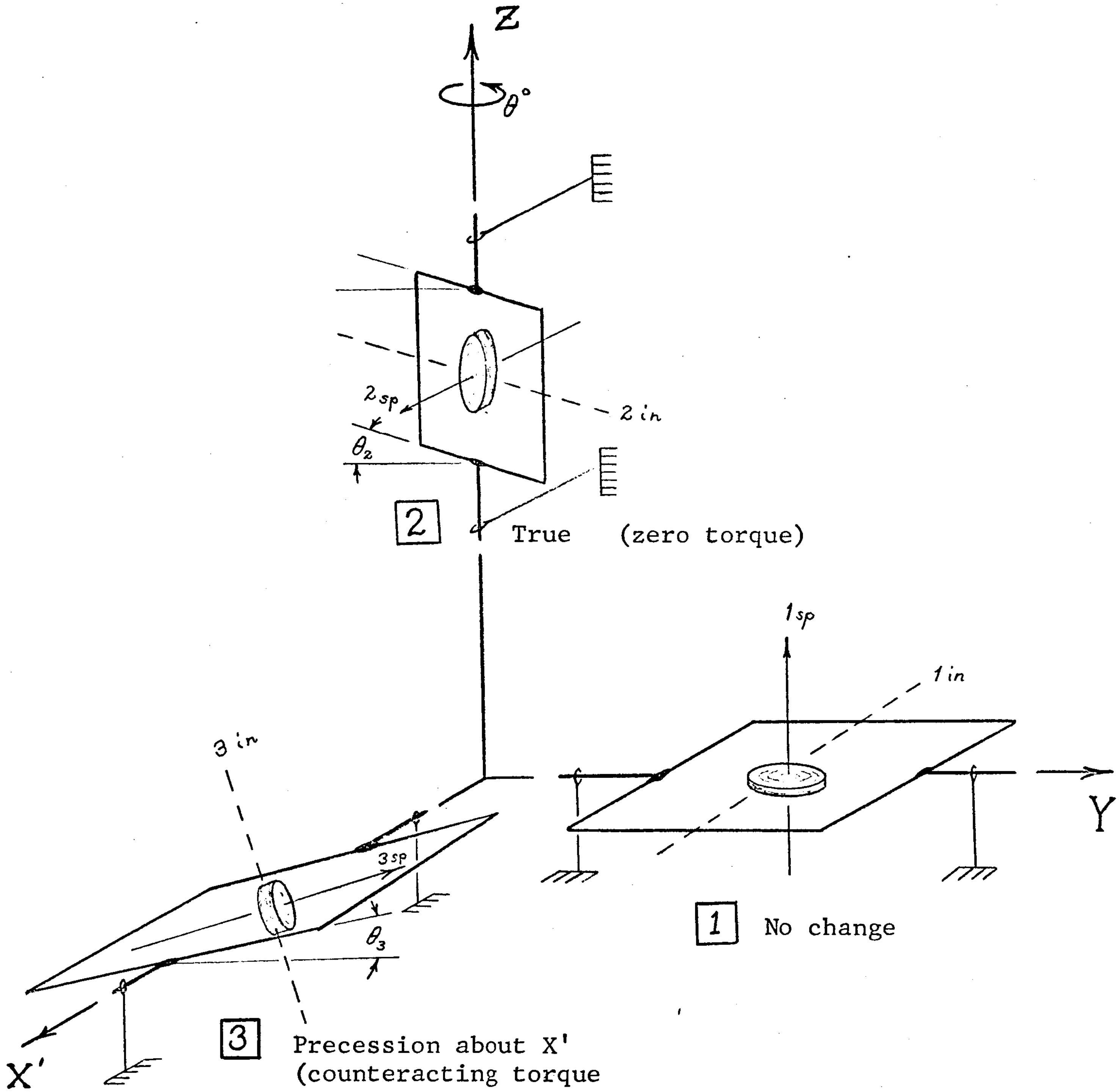


FIGURE 9: Rotation of θ degrees about Z

Task D. Vehicle Configuration, Control, Dynamics, Systems and Propulsion

The objectives of this task are to investigate problems related to the design of a roving vehicle for Mars exploration with respect to configuration; motion and attitude control; obstacle avoidance; control, information and power systems; and propulsion systems. In addition, the design concepts must accommodate the equipment and instruments required to automate the vehicle and to perform the scientific objectives of the mission.

Task D.1. Vehicle Configuration - W.P. Rayfield
Faculty Advisor: Prof. G.N. Sandor

The objective of this task is to define and evaluate a vehicle configuration required to meet mission objectives. During this period, three major activities have been undertaken.

(1) The literature relating to the design of extra terrestrial vehicles has been reviewed in detail with particular attention to the Grumman, Bendix and Lockheed vehicles. This review has provided an insight into various design approaches and has defined areas deserving further study.

(2) A creative design effort considering unusual combinations of processes and devices that might lead to novel design concepts has been completed.

(3) Conceptual and analytical design and preliminary evaluation of systems suggested either by the literature review or the creative design effort has been undertaken.

As a result of these activities, a creative and original vehicle design, MRV, which at the present state of development meets the NASA specifications and which offers some advantages over previously proposed and developed lunar roving vehicle. A scale model has been constructed and updated twice to demonstrate the maneuverability and obstacle avoidance characteristics of the vehicle some of its general features are shown in Figures 10, 11 and 12.

The four-wheeled, unsegmented MRV has a unitized payload. This reduces vehicle weight by requiring a single support frame, eliminating segment couplings, and reducing communication links. This compact configuration facilitates stowage and deployment of the vehicle. The major disadvantage of this feature is the additional insulation and cooling equipment necessary to dissipate generated heat. However, consolidating most components would simplify the problem of insulation from the hostile Martian surroundings (radiation, heat, dust, etc.). The simplified one-frame construction could provide a larger area for mounting solar panels.

While the use of two driven wheels, instead of the segmented vehicles' six, appears to reduce the mission reliability, there are several advantages. The weight thus saved can provide proportionately more powerful, more sophisticated and thus higher reliability electric motors. Since the two drive wheels support 90% of the vehicle weight, the maximum traction produced by the two larger motors and wheels can be equal to that of the six drive wheels on the LRV's. The two drive wheels of the MRV are constantly in contact with the surface; however, while the segmentation of the LRV's maximizes the surface contact of all six wheels, one or more wheels can lose contact during obstacle negotiation at precisely the time when maximum traction is required.

The larger wheels, permitted by the enlarged drive motors, increase the size of most negotiable obstacles. For instance, the 2' radius MRV wheels can cross larger crevasses than the 1'- 6" radius wheels of a six-wheeled, segmented LRV. Although the proposed MRV is limited to a step equal to the radius of its wheels, it seems that its step-climbing ability is comparable to the smaller wheeled segmented vehicle. Another advantage of the larger wheels is the higher ground clearance they provide, although the center of gravity is raised. With fewer wheels and the unitized payload, however, the MRV can provide a wider wheel span than the segmented LRV's, and thus maintain the same stability as the LRV.

The 360° "wagon" steering offers two advantages over the LRV steering systems. First, only a single yoke and bearing system is necessary to turn both wheels. This simplifies the mechanical system as well as the steering control logic. Secondly, the wheels may be turned without scuffing, allowing the wheels to be easily turned when the vehicle is at rest, as well as when moving. This helps prevent the wheels from becoming wedged when on rough terrain. Combining the scuff steering of the rear wheels, turns can be made about the center of gravity of the vehicle (zero-radius turns), eliminating the centrifugal force component that can easily overturn a vehicle on a low-gravity planet.

The weight distribution of MRV is favorable. The primary purpose for the concentration of weight in the rear is to provide the maximum traction for the rear drive wheels. However, this arrangement also facilitates steering, since the front wheels carry the minimum load. Having the same track width and diameter as the rear wheels, the lighter front wheels can provide obstacle measurement for the advancing vehicle; their isolation from the fragile payload also permits their use as a mechanical obstacle detector.

The rear mounted payload has suggested a maneuver which only the MRV can perform. By collapsing the front axle support structure, shortening the wheel base and tilting the rear payload, the center of gravity can be shifted behind the rear wheels, causing the MRV to tip back onto a small fifth wheel. The front wheels can then be raised from the ground while the vehicle turns on the three rear wheels; this permits the vehicle to circumnavigate large obstacles when turning space is limited. The tip-up operation may also aid science stops by placing an instrument package closer to the surface.

The adjustable wheel base may be utilized to increase stability and traction on slopes: extending the front wheels for steady up-grades, withdrawing the wheels for steady down-grades. The hinged structure necessary for this operation can also be employed for vehicle stowage and deployment.

The proposed work for the coming period includes the following:

a) Design and construction of a scale model of a typical Martian landscape.

b) Production of an 8-mm. animated movie to illustrate MRV maneuvering versatility with the present scale model.

c) Development of modeling equations necessary to design an operational scale model to simulate the dynamic characteristics of the full-size vehicle.

Design and construction of working model.

The schedule for the proposed work is shown in Figure 13.

Task D.2. <u>Wheel and Suspension System Design</u> -
G.A. Baxter
Faculty Advisor: Prof. G.N. Sandor

The objective of this task is to design the wheels and suspension system for the mars roving vehicle. Major emphasis during the past period has been directed to work aimed towards suspension systems and possible other related systems on the vehicle is to be undertaken during the coming period.

A major effort to identify creative wheel design concepts has been completed. All conceivable configurations were carefully considered to determine their special applications and relative advantages and disadvantages. As design criteria become more evident it was possible to narrow down the proposed wheel designs. The analysis has reached the point where the next design step will be a trade-off between a small number of similar designs having the same performance specifications.

In addition, there has been investigation into existing wheel designs used on Lunar Roving Vehicle prototypes. The methods of approach to wheel design by Grumman, Bendix, and Lockheed is as important to this task as are the wheel designs themselves. A visit to the Grumman simulated moon plot near Riverhead, N.Y. proved quite interesting and helpful. Wheel testing equipment were demonstrated and the LRV and related equipment were observed.

After research and analysis of several different basic wheel and track designs it was concluded that a flexible metal, spoked wheel with a wide flat rim be used. This configuration adapts itself very well to the type of vehicle design being developed, Task D.1. a number of reasons: It can accommodate a motor in the hub, its compressible spokes and flexible rim provide a large footprint area necessary for good traction and

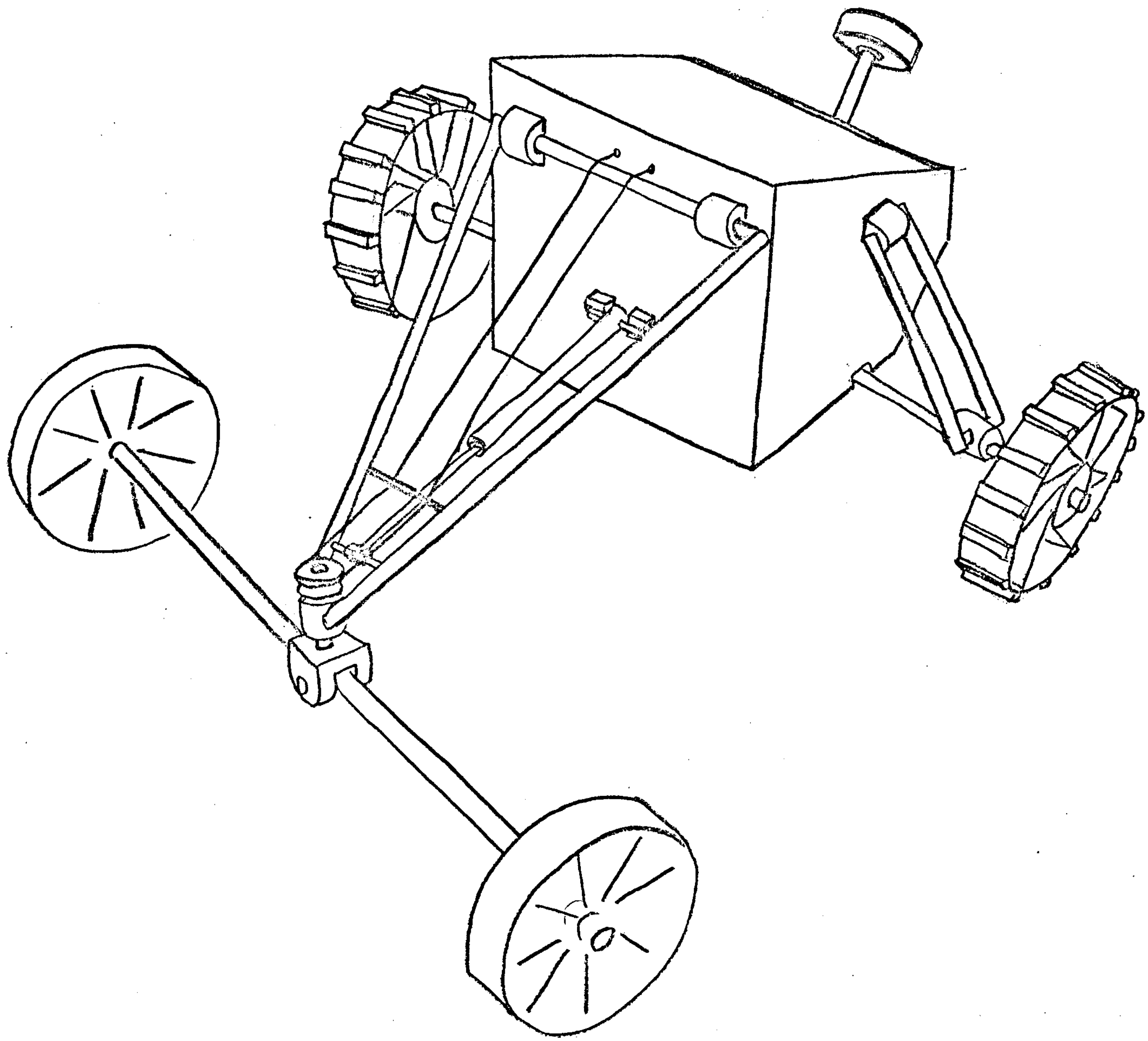


FIGURE 10: Proposed Configuration for Mars Roving Vehicle (MRV).

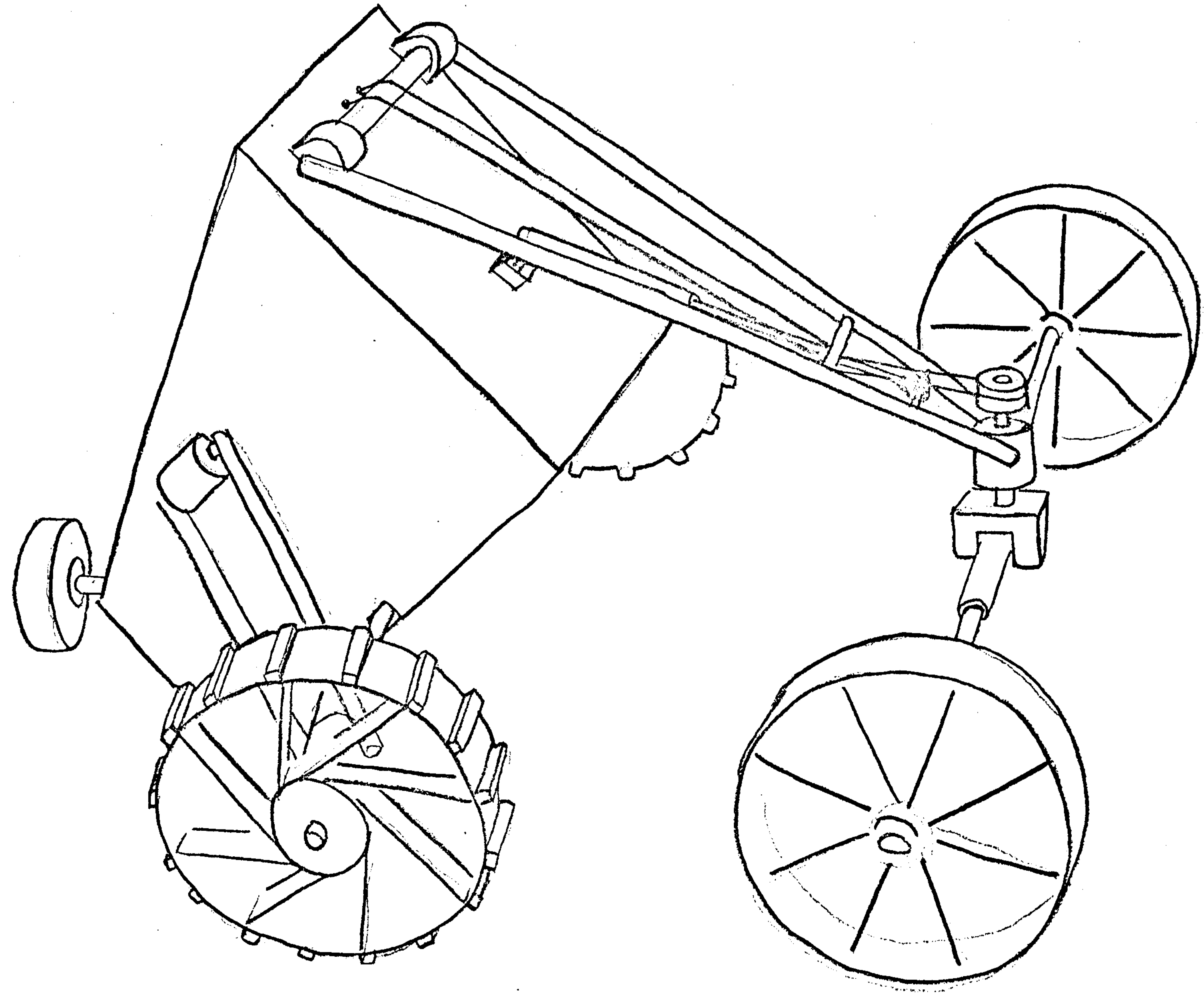


FIGURE 11: MRV's Collapsed Forward Support Structure Shifts Center of Gravity Aft Rear Wheels.

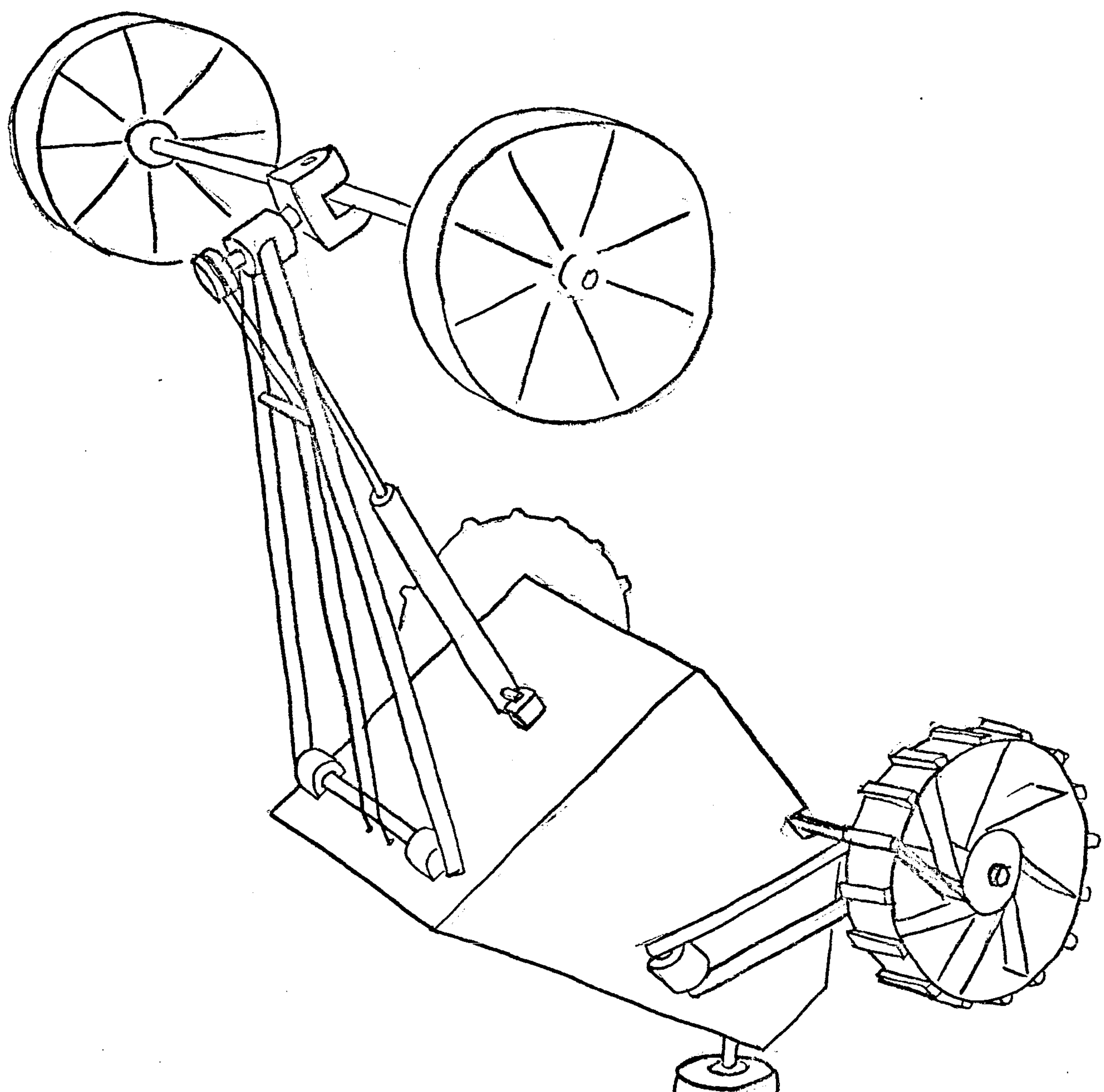
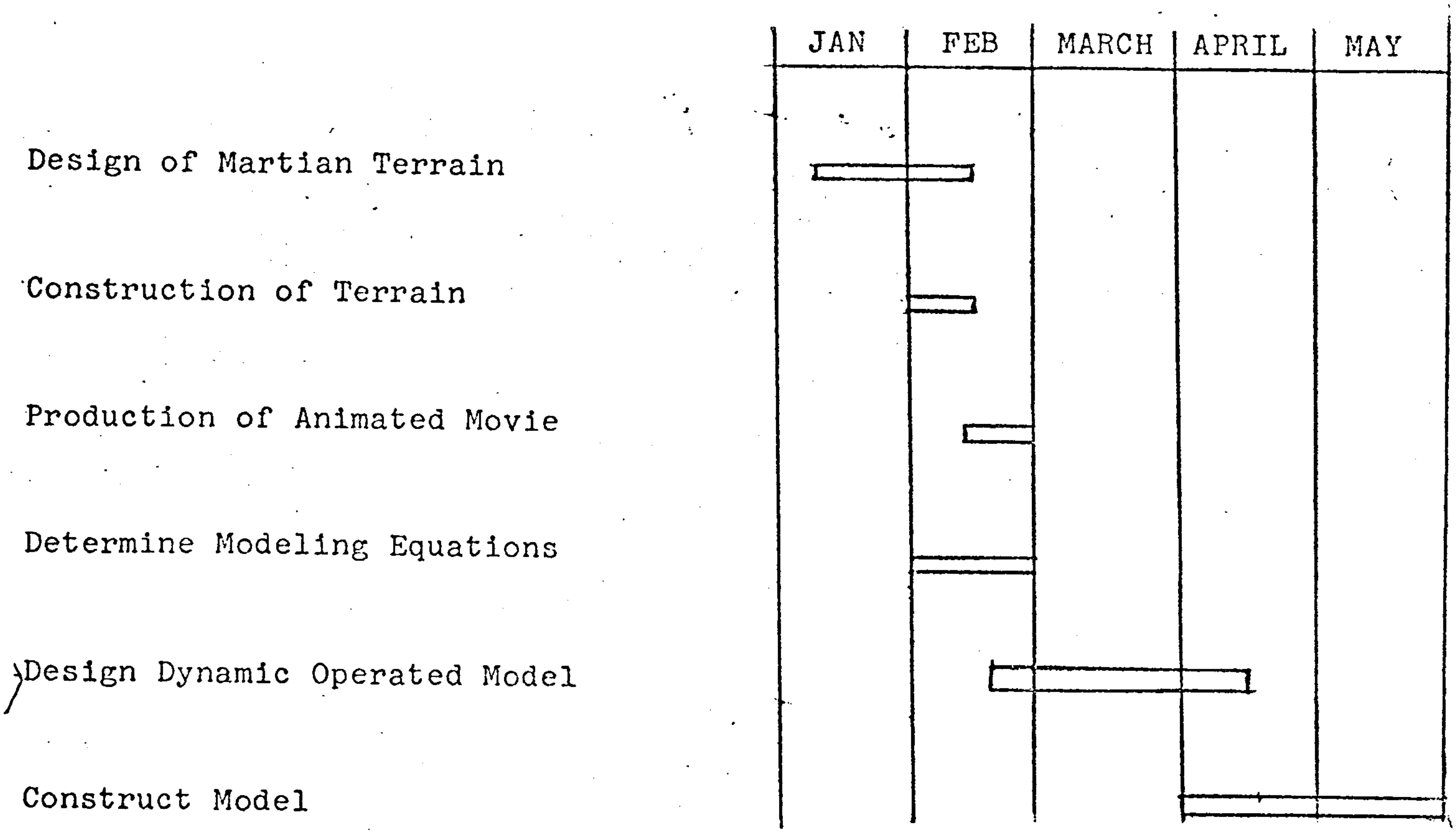


FIGURE 12: MRV's Tip-up Turning Maneuver Avoids Near-by Obstacles.

FIGURE 13: Schedule for Spring Semester, 1970
Mars Roving Vehicle Design



shock absorbtion, the minimal scuffing provides accurate steering, and the danger of micrometeorite tube puncture is eliminated. This wheel lends itself to a rigorous mathematical analysis of its performance characteristics, greatly aiding the design procedure which cannot be supported by extensive working model facilities.

The mathematical analysis was begun with the simplest case of a two spoked wheel with rigid connections between the spokes and the rim. The analysis of even this simple case is quite detailed but the generalization to an n-spoked wheel is rather straight forward. The present task is to adapt the analysis to a wheel with compressible spokes and compare with wheels of other flexible configurations giving the same effect, such as the following: wheels with curved band spokes, circular hoop spokes of spring steel, and hinged segmented rims.

At this point the analysis of the wheel is nearly complete. When it is finished a computer program will be written to give load capacity, spring constant, weight, etc. based on the materials used, size desired and other design parameters. From that point the detailed design can proceed and the wheel can be integrated into the overall suspension system.

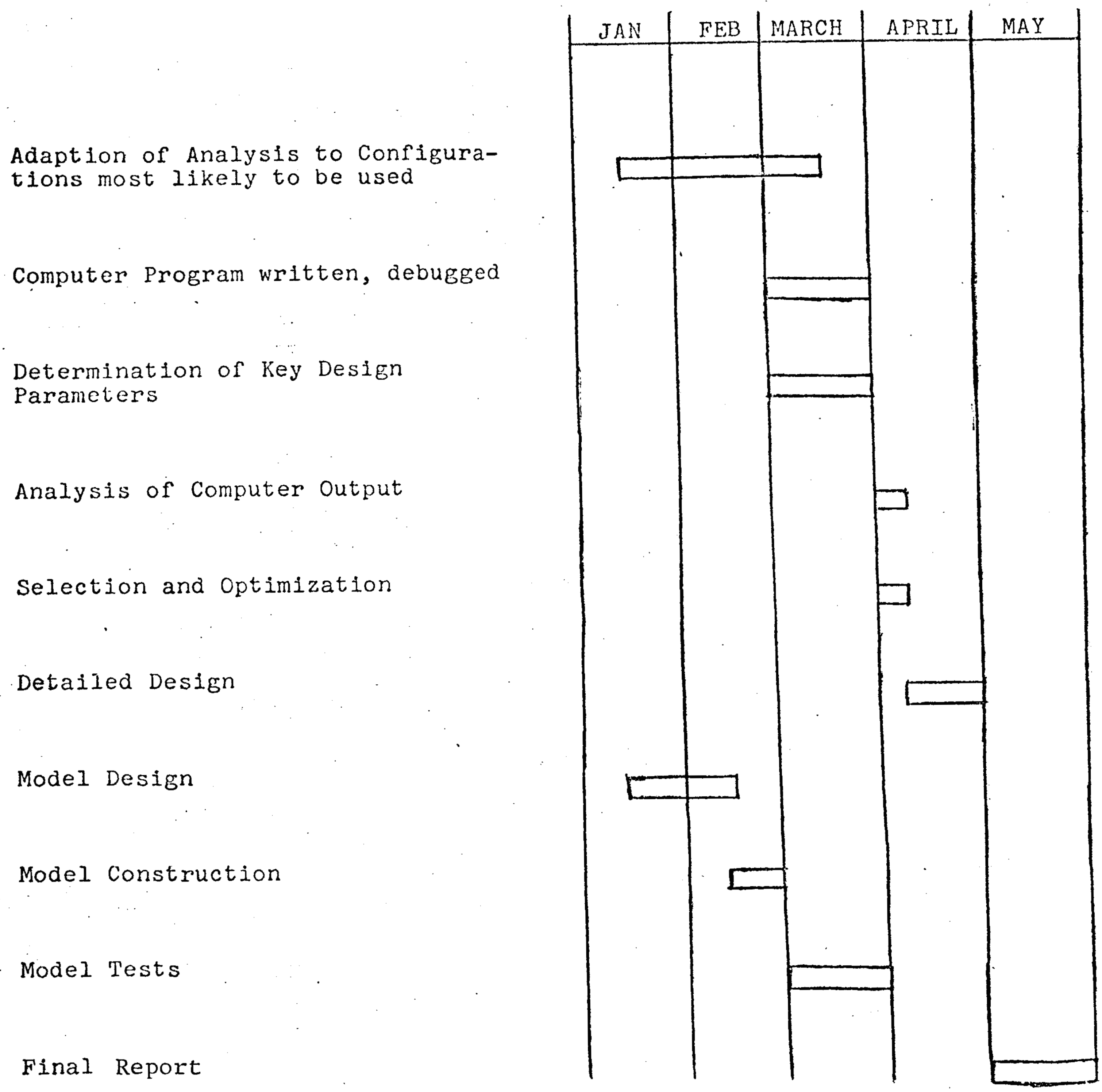
The schedule for work during the coming period is shown in Figure 14.

Task D.3. Auxilliary Propulsion System - M.K. Ho
Faculty Advisor: Prof. C.N. Shen

The reduced gravitational field on the Martian surface poses serious propulsion problems for a roving vehicle. For example, since the gravitational pull at the surface of Mars is about one-third that of the earth, the frictional force available on the wheel for pushing the vehicle forward is only one-third what it would be on this earth assuming that all else is equivalent. Thus a conventional drive may be unable to move the vehicle because of slippage.

It is assumed that in certain parts of the exploration route, the Martian surface is loose and sandy. Using bearing capacity as a criterian it is shown that the conventional vehicle may experience slip sinkage and the traction problem of the landed vehicle becomes more difficult.

FIGURE 14: Schedule for Spring Semester, 1970
MRV Flexible Wheel and Suspension System Design



The primary effort of this work was to provide an auxilliary propulsion system for the vehicle to handle unusual terrain. Cornell University, Grumman Aircraft, and many other groups have studied the propulsion problems of vehicles on hard surface. The results were generally satisfactory, but under the assumption of soft soil a vehicle may experience slip sinkage in the loosened soil. From soil mechanics, it is known that the safe load on the soil is mainly dependent on the coefficient of cohesion. By using bearing capacity of an assumed soil, we have shown that for a certain weight vehicle, this type of failure may occur. To solve this adverse problem, a bladed wheel was suggested. The blades can penetrate into the loose soil and then throw it backward, thereby producing a reaction force in the vehicle propelling it forward. The performance of this kind of bladed wheel in soft soil was analyzed. Numerical results for this type of wheel performance under different terrain conditions were evaluated by an arbitrary assumption of the vehicle parameters. Results indicate that it is feasible to use this design as a means to overcome the propulsion problem in soft soil.

When the vehicle operates on hard surfaces, a fixed blade configuration may cause a vibration problem, and this should be avoided. As an alternative, a passive, retractable bladed wheel was considered. The blades can be compressed back by the hard surface but will be extended and penetrate into the soil when the surface is soft enough that auxilliary propulsion is needed. Thus this retractable bladed wheel can overcome all desired terrain on the Martian exploration route and play the role of an auxilliary propulsion system for a Martian landed vehicle.

The wheel is composed of two parts, the inner part is a modified version of Grumman's metalastic wheel for suspension and damping. The outer part is a second rim with a series of spring-loaded retracting blades projecting out through slots in the outer rim.

The future work will include the detailed analysis of the retractable bladed wheel construction. Coupled with the assumed Martian soil parameters and vehicle design parameters, the general performance of the wheel system will be studied. A comparison will be made between this wheel and the wheel designed under Task D.2.

Task D.4. Vehicle Systems

The design of a roving vehicle for Mars exploration requires that a balanced commitment be made to each of the components of the system including power for propulsion, communication systems, computer, actuators, control and guidance systems, terrain sensors, etc. While each of these components will ultimately require detailed design, interfacing and optimization of these requirements within the general context of the mission is crucial. It is the objective of this task to develop overall concepts, guidelines and quantitative criteria which will provide a rationale for the commitment of payload to various functions.

To date, work has been aimed at developing identifying the major components and functions to be considered and at estimating some first order allocation to them. A preliminary breakdown of allocation is shown in Table 2.

TABLE 2

Total MRV weight		900 - 1000 lbs. (earth)
		Per cent of Total MRV Weight
Instrument Package		40 - 60*
a)	Experimental Package	10 - 14
b)	Power Sources	15 - 20
c)	Communications	10 - 12
d)	Guidance	5 - 10
e)	Contingency	0 - 4

* The higher values reflect present design trends, Task D.1., toward a lighter vehicle in terms of structure, wheels, and propulsion and steering systems.

During the coming period efforts will be directed to the evaluation of on board systems in terms of different mission objectives. For example, vehicle weight allocations may be significantly altered if maximum distance is not given the same priority as the number of experiments to be conducted.

Task D.4.a. Power Systems for Martian Roving Vehicle - J. Grupe'
Faculty Advisor: Prof. G.N. Sandor

The initial concept of this project was to develop a suitable power source for propelling a landed Martian vehicle across the surface. As this problem was investigated, it was decided to alter the goal to the development a flexible systems analysis of the power supply and related mechanical components.

The solutions sought are methods of determining the total and relative quantities of each component, of determining when and if additional or replacement components should be employed, of specifying the placement of components for maximum efficiency, and of controlling the overall system to maximum effect.

The problem of surface propulsion was divided into two parts, power sources (meaning the energy storage units) and motive power (meaning the conversion of energy into a usable mechanical output). In each category, a survey of all possible components was made and rough analysis of their feasibility studied. The conclusions reached were that the eventual system would rely on electric drive motors powered by a combination of RTG (Radioisotope thermal generator) and rechargeable batteries. The possibility of included an anemometer-driven flywheel generator is being investigated, but only as a supplemental power unit until its reliability is proven such that it could replace other units. Solar cells are also being considered for use as supplemental energy sources, though not as a prime system. The reason for this decision is the high probability that solar cells will experience a rapid loss of efficiency due to dust and the already low potential output on Mars. It is possible however that a type of solar panel may be used as both energy source and enclosure for the rear compartment, adding power but little or no weight to the overall design.

To achieve the objectives of this task, it is necessary to develop a mathematical model which can demonstrate the effects of each vehicle parameter and their interelationships. To date a simplified version has been developed for a model in which time for recharging batteries and time available for vehicle motion are incorporated. Factors such as vehicle velocity, terrain features resulting in variable power requirements, battery discharge are being simulated.

To these simplified equations will be added other parameters, such as the deterioration of the batteries and RTG with time and recharge cycles.

The graphs relating required recharge time, and allowed traverse time, to other vehicle and mission parameters will be ready early in February, 1970, and additional detail will be added during the month. The variations in parameters due to deterioration and/or other time dependent factors will be incorporated in March. By June, 1970 a completed set of equations and corresponding patching diagrams for the analog computer will be ready relating all ofthe known parameters which will have an effect on the power supply and its capabilities.

Control systems for the power supply and related vehicle mechanical systems are now entering consideration. Also, the placement of components, where necessary, is to be specified as closely as possible. Progress in both these areas is greatly dependent on the information available from other design groups, it should be possible to relate the power supply and controls, and interrelate these two areas by April, 1970.

Task E. Chromatographic Systems Analysis

One important phase of the initial missions to Mars is the search for organic matter and living organisms on the martian surface. The present concept for attaining this objective consists of chemically treating samples of the atmosphere and surface matter and thereafter analyzing the resulting products, probably in a combination gas chromatograph/mass spectrometer. It is the objective of this task to generate fundamental engineering design techniques and concepts for use in optimizing the design of the chromatographic separation system.

Because of the variety of mixtures to be separated and the complexity of the separating process, a systems analysis based on the mathematical simulation of the chromatograph is being undertaken. This technique will use mathematical models, which incorporate fundamental parameters, to explore various concepts and to direct further experimental research.

A mathematical model, composed of a system of partial differential equations, was presented earlier (Ref. 10).

This model assumed that the sample material was transported in the axial direction (direction of carrier gas flow) of the chromatographic column by bulk transport in the carrier gas as well as by diffusion under the influence of a composition gradient. Transport to and from the adsorbent surface was assumed that no transport resistance resided in the adsorbent phase. The system equations showed that the carrier gas composition was a function of time and three dimensionless column parameters:

Pe - the Peclet number which is a dimensionless measure of diffusion or dispersion in the direction of carrier gas flow.

N_{tOG} - a mass transfer number related to the approach to equilibrium adsorption and directly proportional to the column length.

mR_o - a thermodynamic parameter, m being the adsorption constant and R_o being the ratio of the amount of gas to the amount of adsorbent in the column.

Of these parameters, mR_o is specific to each chemical system, whereas Pe and N_{tOG} depend primarily upon the physical characteristics of the system (particle size, carrier gas velocity, etc.). Prior work, Ref. 10 and 12, showed that neglecting axial diffusion, while simplifying the system equations, was not valid when comparing the numerical results with experimental data. In addition, it was found (Ref. 12 that the technique by which the sample was injected strongly influenced the results under certain conditions. Currently the project involves the investigation of three areas:

1. Numerical solution of the system equations which include the axial diffusion term.

2. Development of methods for reliably predicting the column parameters Pe and N_{tOG}.

3. Construction of a testing facility to experimentally evaluate the model.

Task E.1. Analysis of System Equations - P.N. Taylor
Faculty Advisor: Prof. P.K. Lashmet

The system equations have not been solved in convenient form. Lapidus and Amundson (Ref. 13) obtained a general solution using Laplace transform techniques, but did not numerically evaluate their results. Adaptation of the solution to this situation gave:

$$y(\theta) = (A/2)\sqrt{Pe/\pi}\ \exp(Pe/2)\ \exp(-N_{tOG}mR_o)\cdot$$

$$\frac{d}{d\theta}\int_0^{\theta} \frac{I_0(2\sqrt{N_{tOG}^2\ mR_o(\ -x)x})\exp(-Pe/4x-N_{tOG}(1-mR_o)x-xPe/4)dx}{\sqrt{x^3}}$$

in which

y = gas composition
A = sample input, considered to be an impulse
θ = dimensionless time
I_0 = modified Bessel function of first kind and of order zero

Because of the complexity of this equation, statistical moments, which can be obtained directly from the Laplace transforms of the solution, were used to gain an insight into the effects of the various parameters on the gross characteristics of the chromatograph curve. These characteristics included the time for the maximum composition to appear and the spreading of the curve about this peak.

Voytus (Ref. 11) studied the system under the conditions that N_{tOG} was very large. This meant the column was infinitely long or that the adsorption process was at equilibrium. This meant the column was infitely long or that the adsorption process was at equilibrium. He found that the mean time $\bar{\theta}$ of the chromatographic signal was dependent only upon the thermodynamic properties of the system:

$$\bar{\theta} = 1 + (1/mR_o)$$

He further found that the deviation between this mean time and the time when the maximum composition appeared θ_{max} could be correlated with the parameters Pe and mR_o using statistical moments. In most instances, the difference between these two times was negligible. Application of this correlation to the non-equilibrium situation of the present study predicted that N_{tOG} would have a negligible effect upon θ_{max} (Fig. 15). This is a useful preliminary result which will be tested when the system equations are evaluated numerically.

To determine the degree of peak spreading, Voytus studied the variance σ^2_{max} of the curve about the maximum point. The variance was expressed in terms of the second and third time moments which were evaluated directly from the Laplace transform of the equation solution. He found that at least 94% of the area of the chromatogram was encompassed by the time interval ($\Theta_{max} \pm 2\,\sigma_{max}$), if N_{tOG} was infinite. Figure 16 shows the estimated effect of finite N_{tOG} upon σ_{max} for two values of Pe. It is noticed that at high Pe, or for small diffusional effects, changes in N_{tOG} have a greater effect on σ_{max} than identical N_{tOG} changes for low values of Pe (appreciable axial diffusion). Under these conditions, the equilibrium adsorption model would have given the following values:

Pe	σ_{max}
30	1.61
300	0.49

Thus these preliminary studies show considerable spreading in the chromatograph curve at low values of N_{tOG}.

These qualitative results will be useful in the numerical evaluation of the system equation. Future work will include evaluation of the equation, testing of the moment techniques which were assumed to apply, and comparing the numerical results with experimental data from known systems. If the model proves to be accurate, work will begin on the multicomponent system prediction.

Task E.2. <u>Transport Parameter Estimation</u> - D.A. Reichman
Faculty Advisor: Prof. P.K. Lashmet

The usefulness of the system equations for design purposes will depend upon the availability of methods estimating the transport parameters, N_{tOG} and Pe. Methods for estimating N_{tOG} have been discussed earlier (Ref. 10) so this task has as its objective the development of a suitability accurate method for the estimation of the Peclet number Pe.

The Peclet number, which is a dimensionless measure of diffusion or dispersion in the direction of carrier gas flow, is defined as

$$Pe = vL/D$$

in which:

- v = mean velocity of the carrier gas
- L = column length
- D = effective diffusion constant

This Peclet number is a function of the fluid mechanics of the system as measured by the dimensionless Reynolds number

$$Re = dv\rho/\mu$$

in which:

- d = particle diameter
- ρ = carrier gas density
- μ = carrier gas viscosity

The physical properties of the gas as expressed by the dimensionless Schmidt number

$$Sc = \mu/\rho D_v$$

in which:

- D_v = molecular diffusion constant

also affect the Peclet number.

Initial investigations of the random-walk and other geometric models of dispersion (Ref. 14 and 15) showed the theoretical models to yield only an order of magnitude estimate for the Peclet number. A literature search revealed little data available for conditions under which the chromatographic columns would operate. The estimation technique finally chosen was a method developed by Johnson (Ref. 16). This model compares two dispersion models through their statistical moments to arrive at an estimate of the Peclet number. The resulting equation is of the form

$$\frac{1}{Pe} \cdot \frac{L}{d} = \frac{2/3}{ReSc} + 0.091 + \frac{h\,\delta^2/4}{\frac{2/3}{ReSc} + 0.091}$$

in which:

- δ = aspect ratio, d_t/d
- d_t = diameter of chromatograph tubing
- h = dimensionless velocity factor

The dimensionless velocity factor depends upon the velocity distribution within the bed and may be estimated by the method of Rhodes (Ref. 17).

Attempts to compute values of the Peclet number from this equation were not completely successful (Ref. 18). For certain parameter values, the Peclet number became negative, a physical impossibility. It appeared that these numerical instabilities arose in the computation of the velocity profile and in the evaluation of the velocity factor h. The specific source of instability has not been isolated and a more thorough investigation of the numerical techniques is now being undertaken. It is expected that these difficulties can be resolved by mid-spring. Completion of the task, which will include design curves as well as the computation technique, is expected by June 1970.

Task E.3. Chromatographic Test Facility - S.R. Baer
Faculty Advisor: Prof. P.K. Lashmet

To experimentally evaluate the mathematical models, a test facility is being constructed by renovating and modifying a Perkin-Elmer, Model 154-C vapor fractometer previously used in chemical kinetics studies. Extensive modifications are required in two areas: the composition detecting system and the sample injection - column mounting system.

Because model verification requires accurate composition detection, especially at the input to the column (Ref. 12), two microthermistor detectors (Carle Instrument Company) will be provided, one for each end of the chromatograph column. These detectors, which have time constants in the order of 0.04 second, will form branches of two separate DC Wheatstone bridges. Because the detectors are more sensitive than those previously used in the equipment, it has been necessary to completely redesign the bridge circuits. Bridge unbalance will be detected by a conventional selfbalancing potentiometer (Leeds and Northrup) during initial measurements and by a light-beam oscillograph (Honeywell) during the final measurements.

The chromatograph is being designed to accommodate the more conventional columns as well as microcolumns which have been proposed for space applications (Ref. 19). This necessitates a new column mounting system which has a minimum of dead volume in order to use the response characteristics of the microdetectors. In addition, injection of the sample by mechanical means rather than by conventional gas or liquid syringe is being considered. Such arrangement would provide more uniform sample signals and permit the use of smaller samples.

Much of the redesign has been completed and the major items of equipment have been procured or are on order. The system should be operational by June 1970.

IV. Projections of Activity for the Period January 1, 1970 to June 30, 1970

1. A report summarizing the studies completed on atmospheric parameter updating and adaptive trajectory control will be prepared. No further work on these tasks is anticipated.

2. The feasibility of the rotary wing concept for unpowered aerodynamic landing will be determined. The decision as to further work along these lines will depend not only on the outcome of this study but also on the question of allocation of resources between this task and other tasks.

3. Emphasis will continue to be directed to problems related to terrain modeling for purposes of defining terrain sensor requirements and developing and evaluating path selection algorithms.

4. The use of Mars orbiters for navigation of the mobile vehicle will be investigated. Alternative concepts by which to implement navigation goals and the instrument requirements of such concepts will be studied.

5. A major effort relating to the design of a mobile vehicle will be continued. Problems related to vehicle configuration, propulsion, power sources, suspension system, vehicle stability, control and guidance will be considered.

6. The chromatographic system studies will be extended to include: evaluation of theoretical models including experimental studies, multicomponent separations problems, and the effect of large amounts of solvent upon the detection of minute quantities of materials.

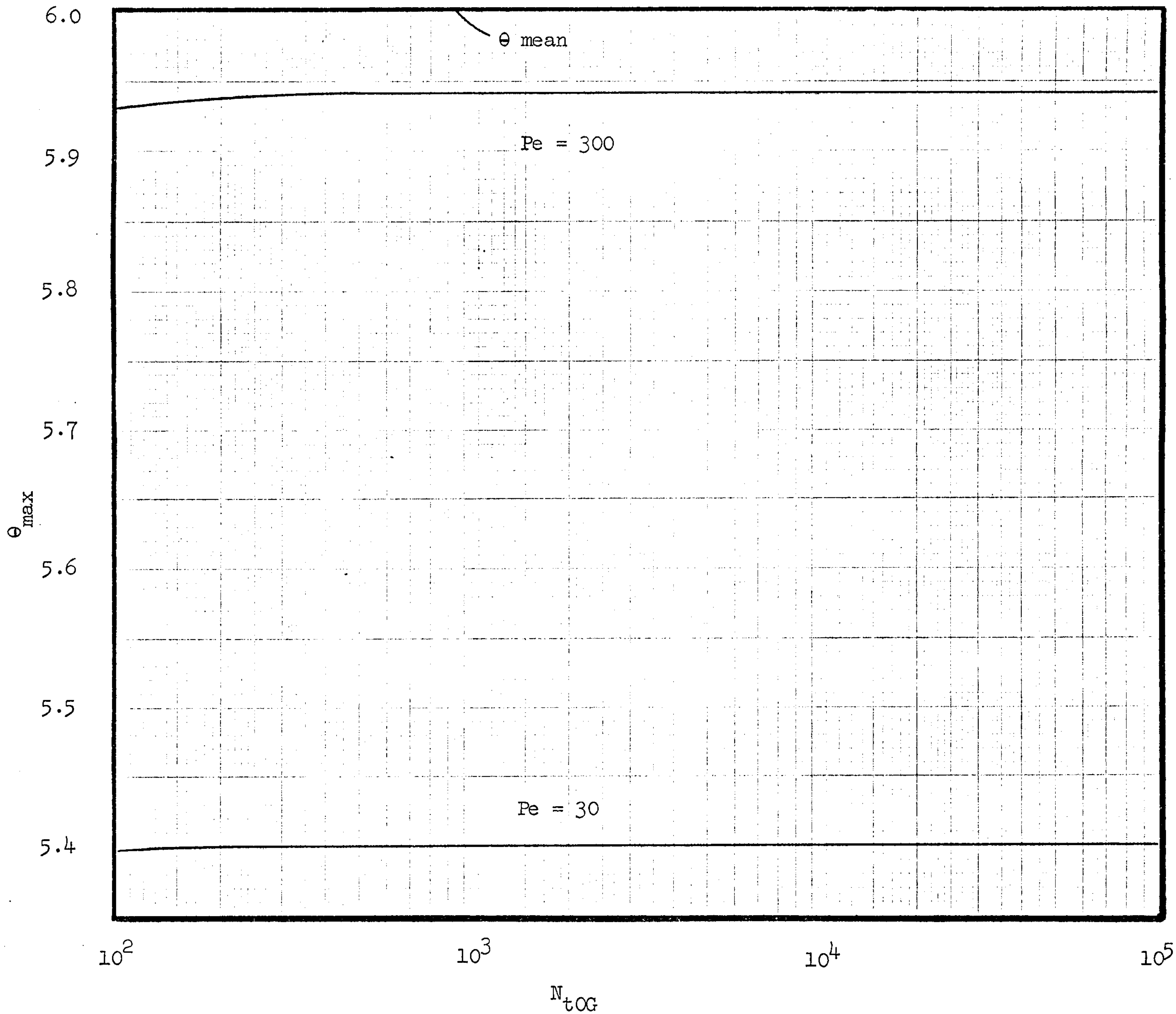


Figure 15: Effect of N_{tOG} on Θ_{max} for $mR_o = 0.20$

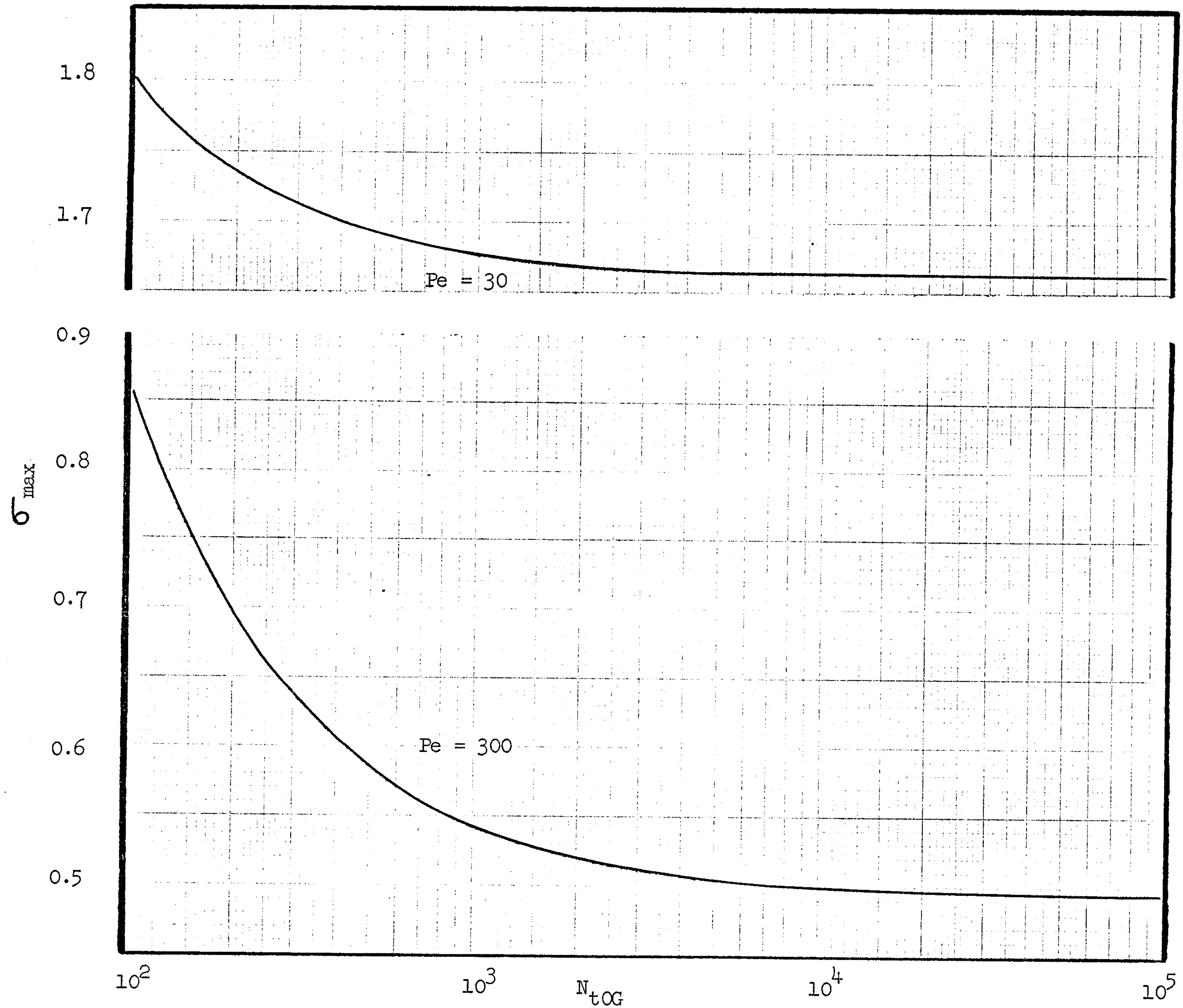


Figure 16: Effect of N_{tOG} on σ_{max} for $mR_o = 0.20$

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